Material Migration Patterns and Overview of First Surface Analysis of the JET ITER-like Wall

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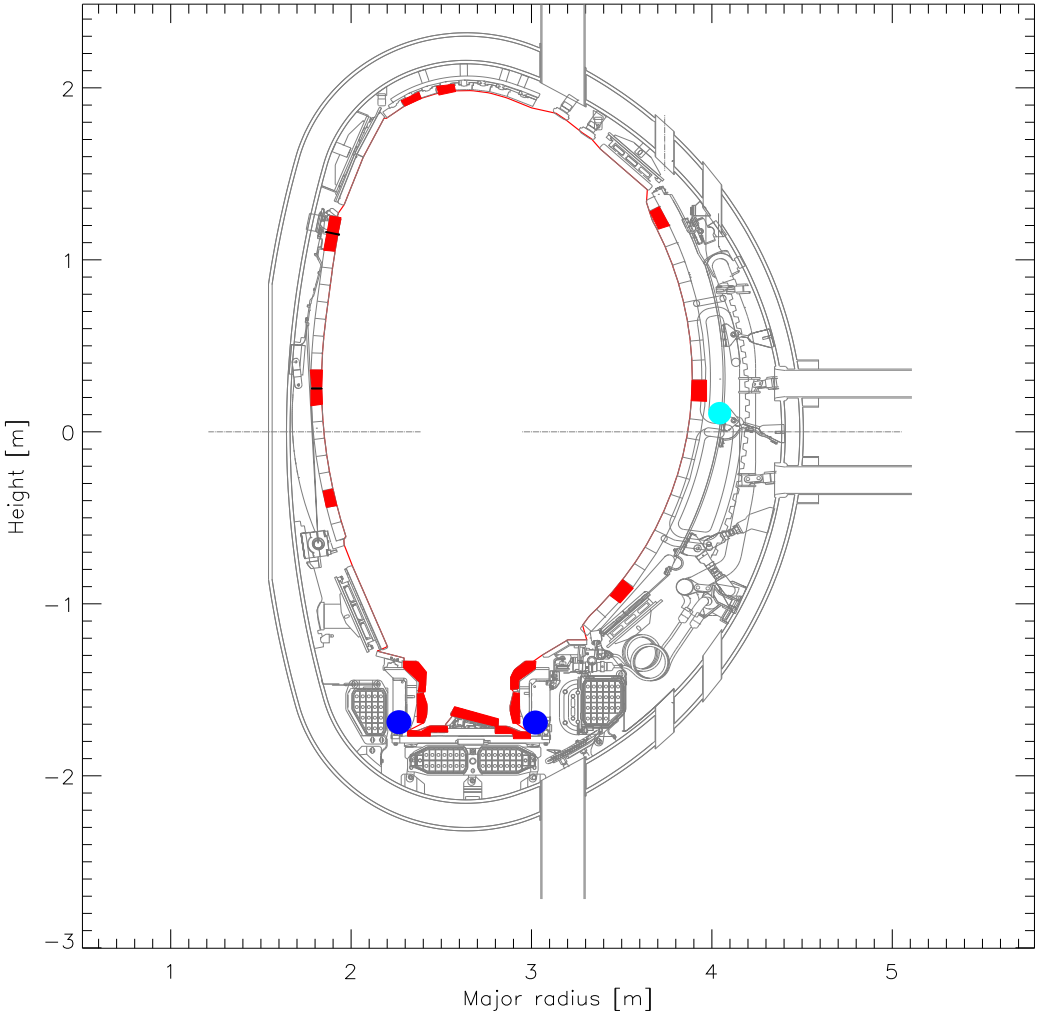
Introduction

- First JET ITER-Like Wall Campaign 2011-2012
- Intervention
  - Remove and replace tiles from divertor and main chamber
  - Remove and replace erosion/deposition diagnostics
  - Detailed in-vessel photographic survey

JET Material Migration Diagnostics and Analysis



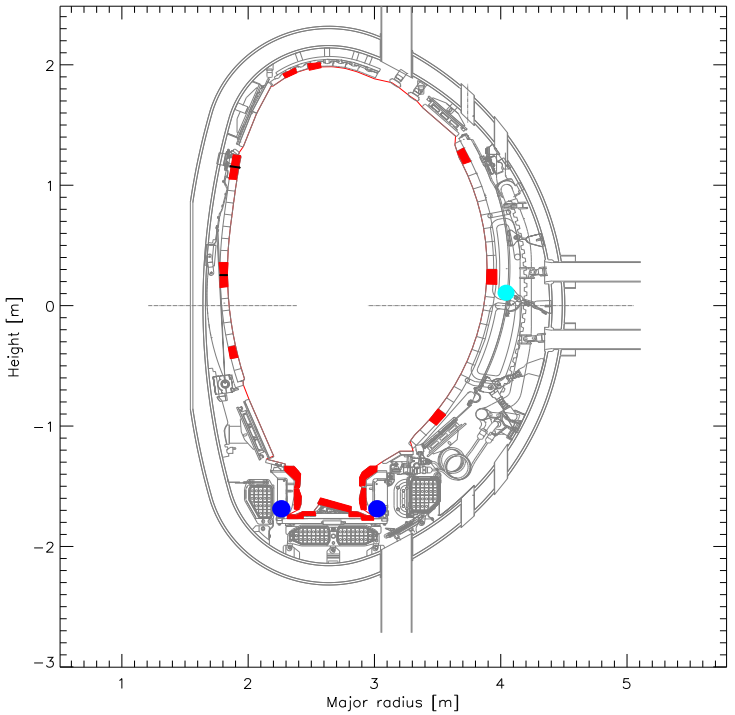
- Marker tiles
- Passive diagnostics in remote divertor: Rotating collectors, Test mirrors, louvre clips
- Passive diagnostics outer wall: Rotating collectors, Test mirrors, louvre clips

•Post-mortem analysis of tiles and diagnostics is an on-going analysis programme lasting 2 years

•First results from inner wall limiters and divertor

Tour of the torus

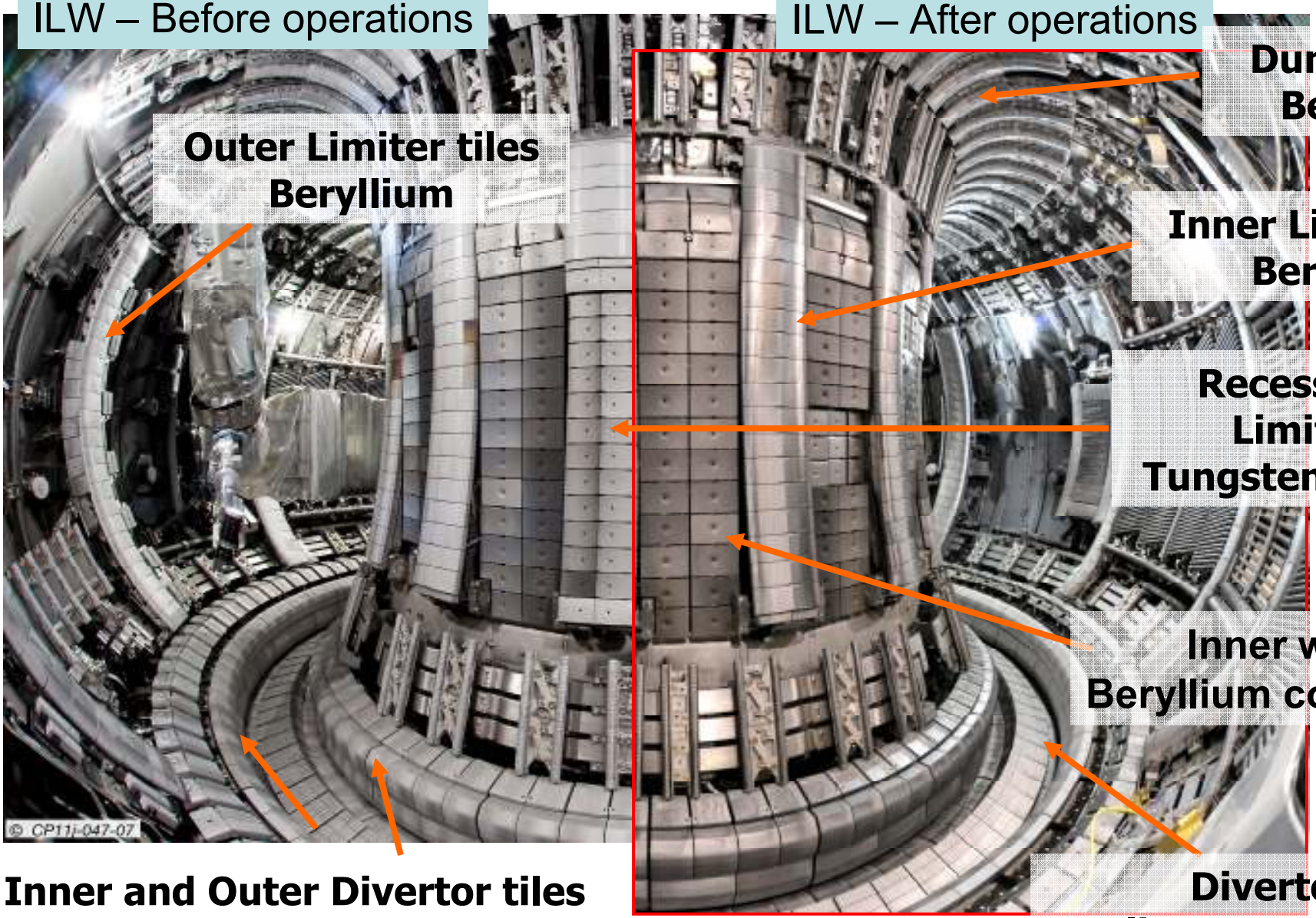
- Changes to tiles during the ILW campaigns
- First erosion and deposition data on tiles removed
  - Inner Wall Guard limiters
  - Dump plates
  - Outer Poloidal Limiters
  - Divertor tiles
  - Diagnostics in remote areas



In-vessel Overview: Spot the Difference

ILW – Before operations

ILW – After operations



Outer Limiter tiles
Beryllium

Dump Plates
Beryllium

Inner Limiter tiles
Beryllium

Recessed Inner
Limiter tiles
Tungsten coated CFC

Inner wall tiles
Beryllium coated Inconel

Inner and Outer Divertor tiles
Tungsten coated CFC

Divertor tile
Bulk Tungsten Lamellae

Campaign statistics

	Total plasma time (h)	X-point (h)	Limiter (h)
2005-2007	35	27	8
2008-2009	45	33	12
2011-2012	19	13	6

- During ILW operations there were dedicated limited plasma to understand the limits of the beryllium wall

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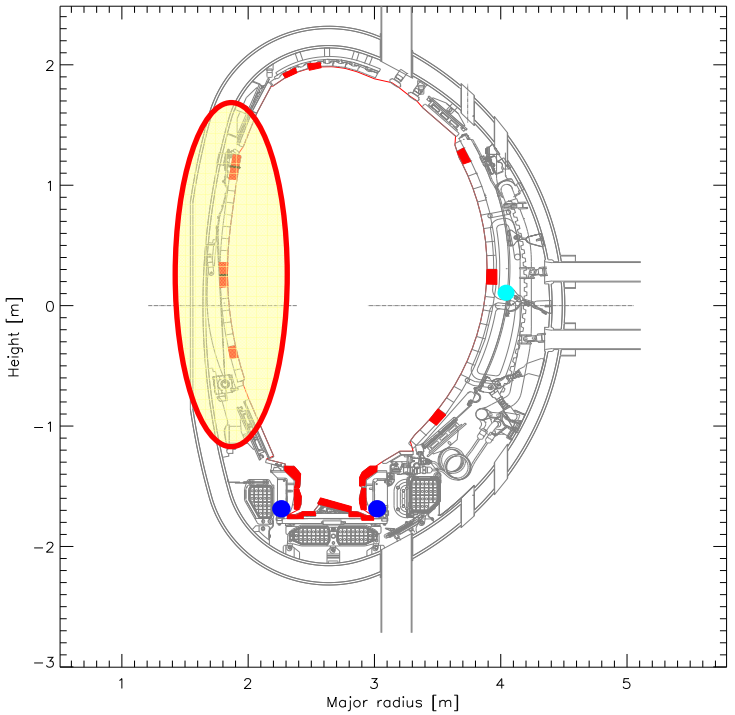
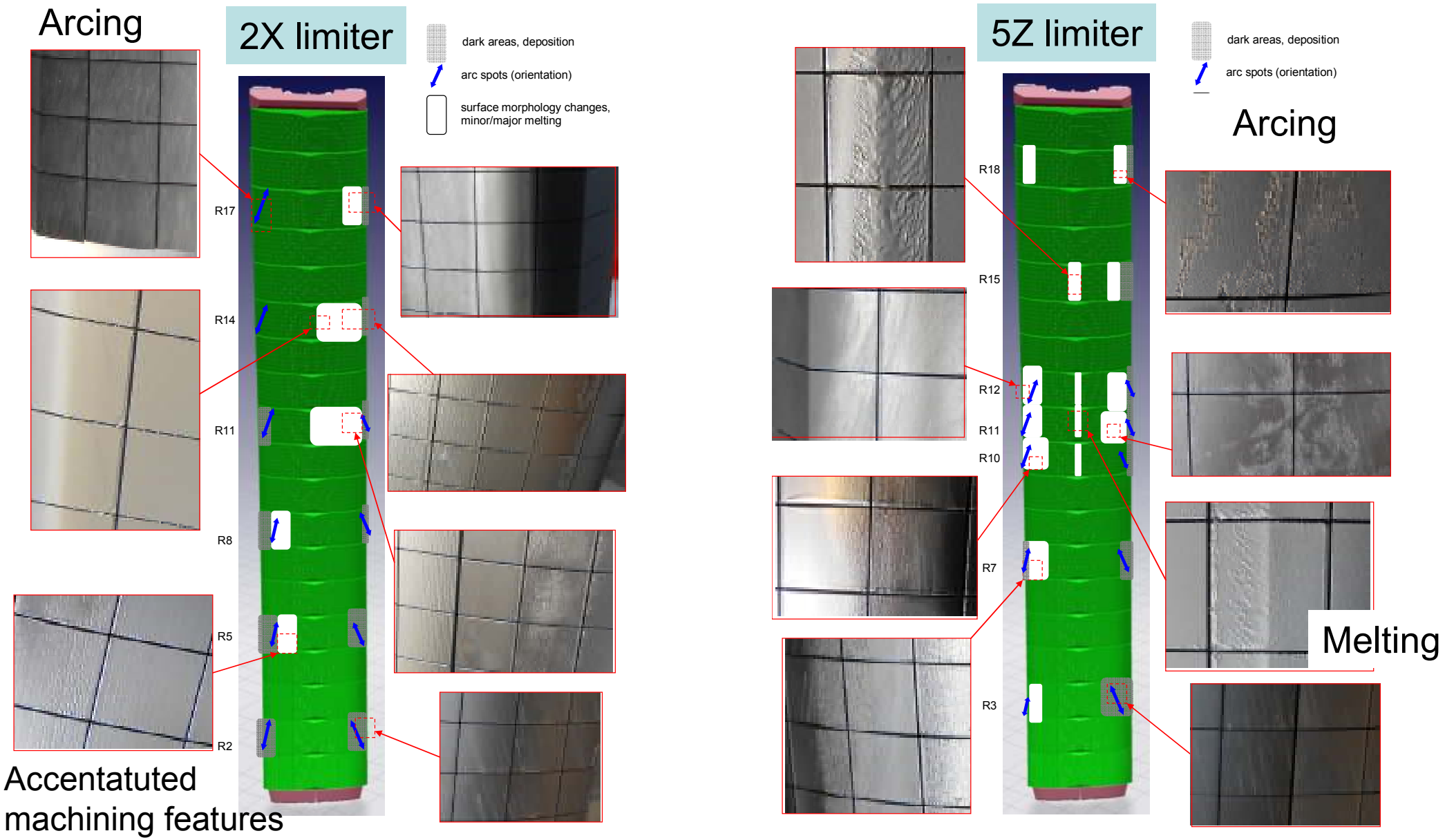


IWGL Morphology



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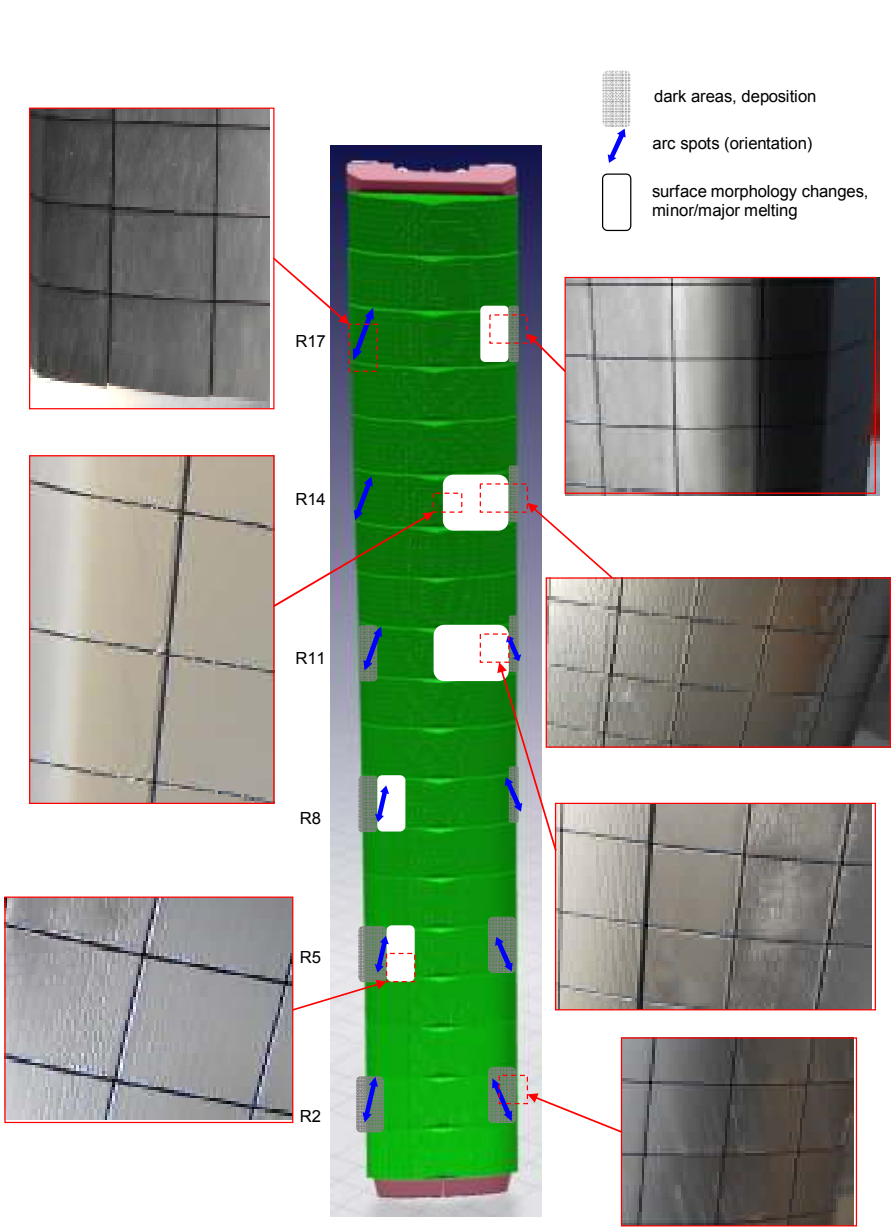
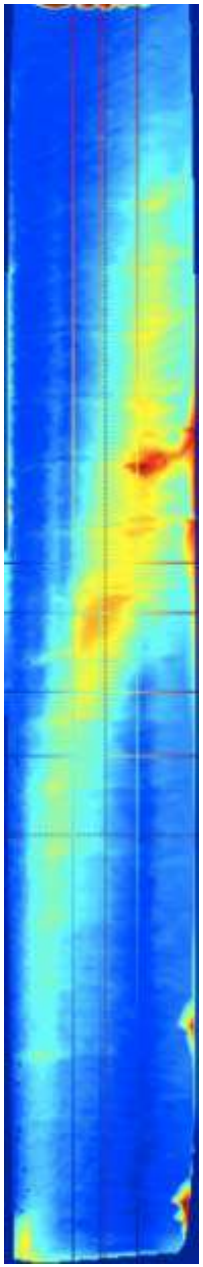
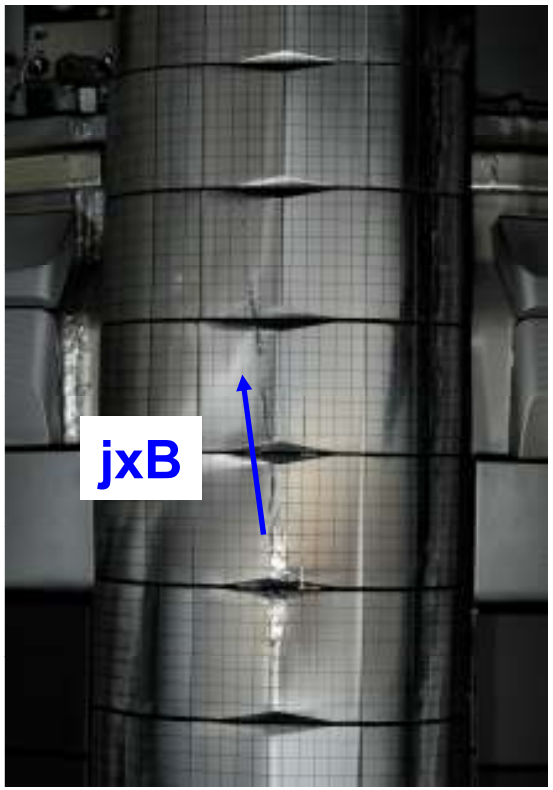




- Melting occurs during limiter phase
- More limiter only plasmas to test the wall

Heat Flux Distribution
Arnoux: PFMC14 I-14

IWGL Melting



4X Limiter

8X Limiter

- Strong melting on two limiters during one pulse to test Be wall
- The melt position is consistent with the contact point
- The melt material driven up by Lorentz jxB forces
- Melt flow can travel a considerable distance upwards even jumping across gaps
- Maximum temperature of 920^{o}C was recorded at melting

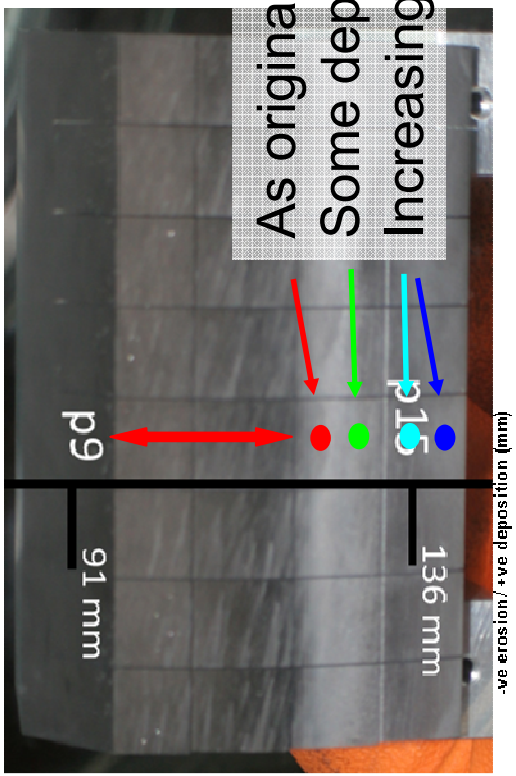
Sergienko PFMC-14
Arnoux: PFMC-14 I-14

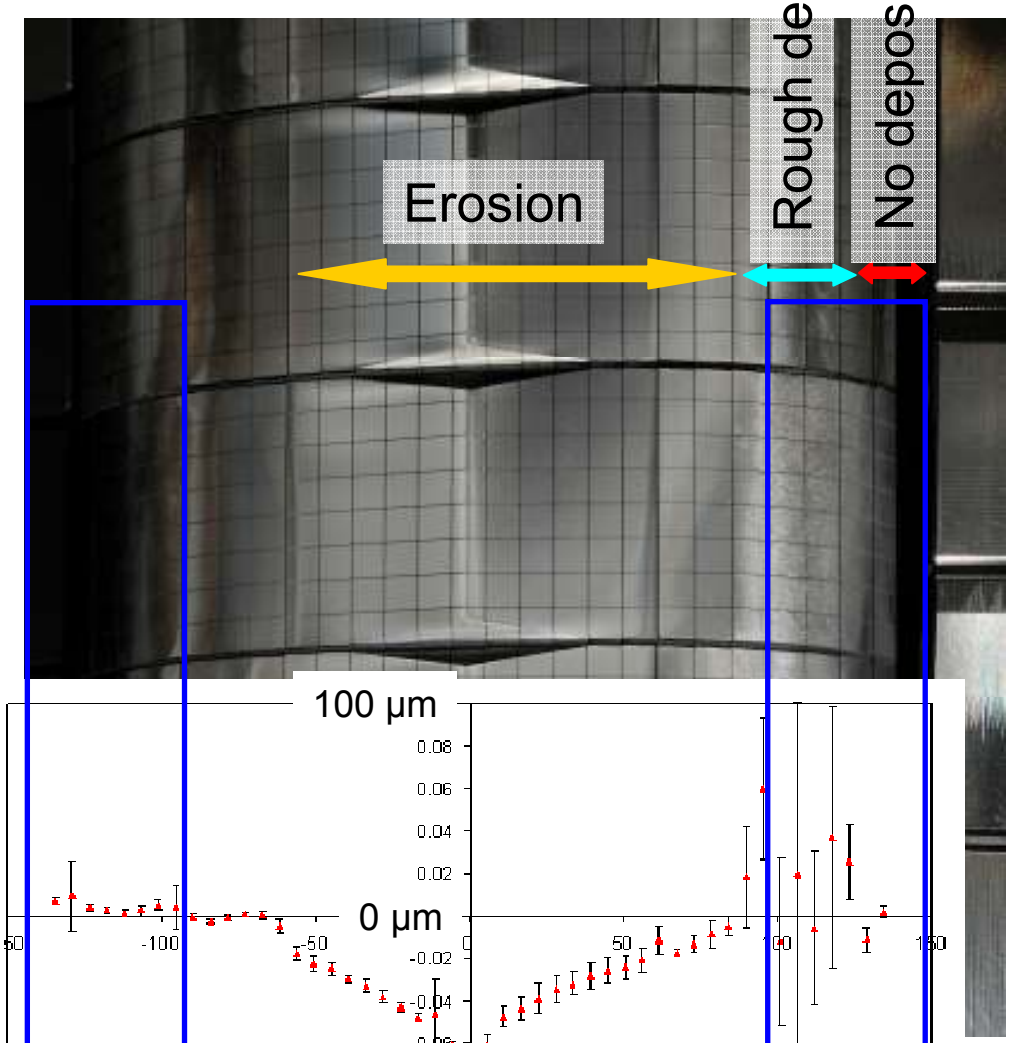
IWGL Results

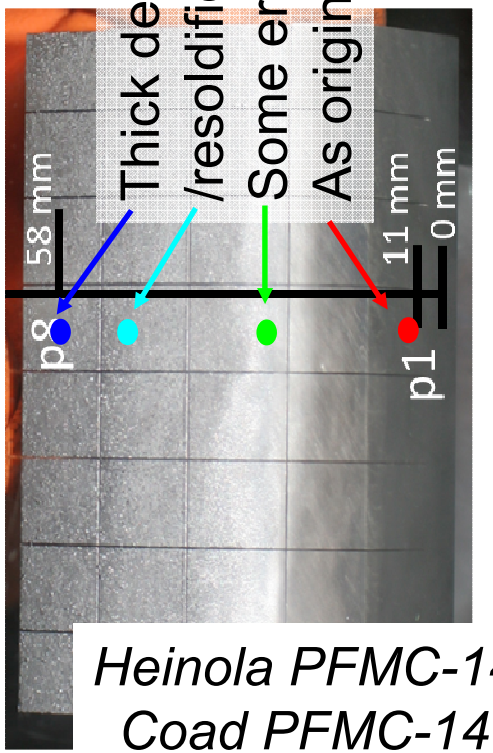
Ion Beam Analysis

SURFACE PROFILING

IBA



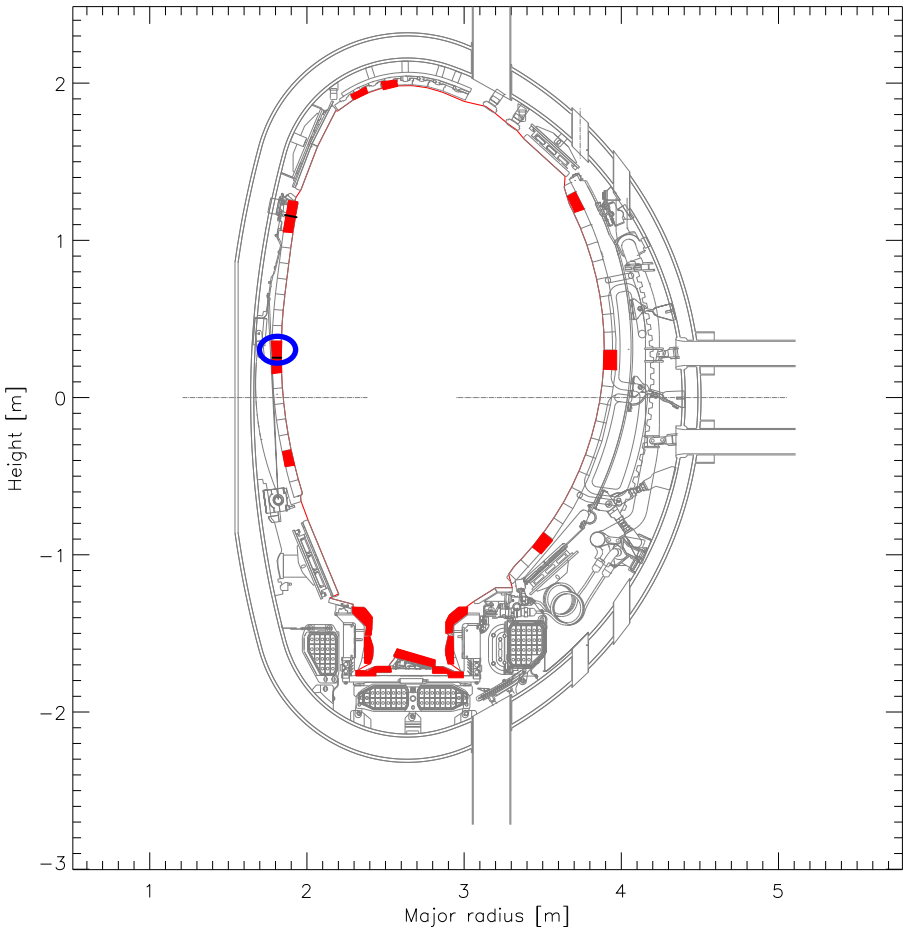


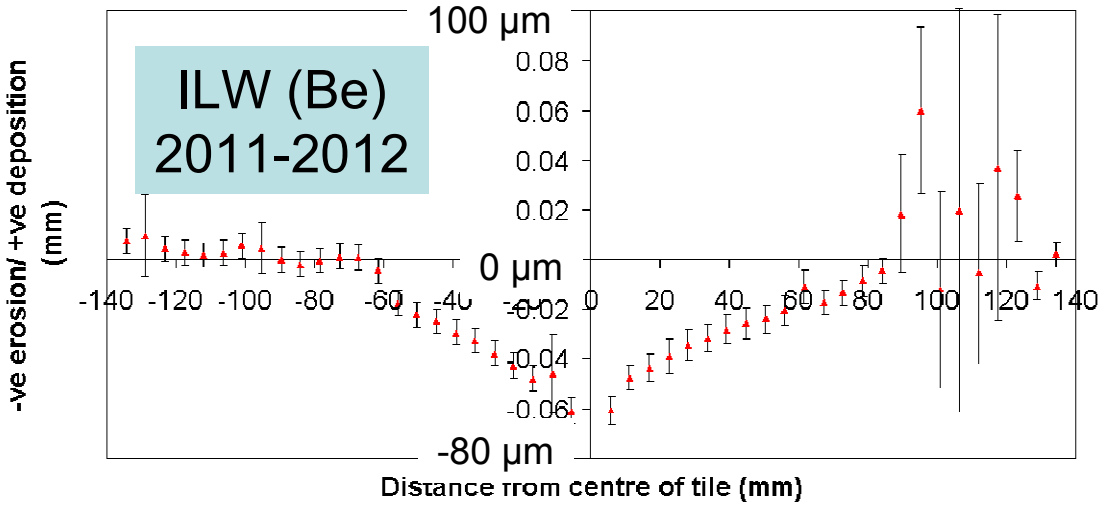


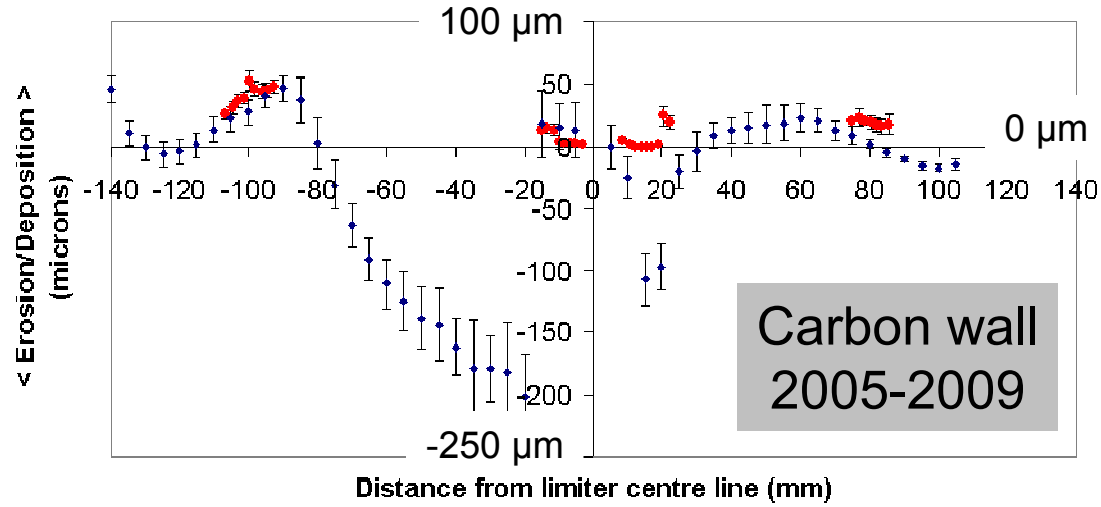
Heinola PFMC-14
Coad PFMC-14

Inner Wall Guard Limiter Erosion and Deposition Beryllium vs Carbon

Comparison of erosion and deposition on mid-plane IWGL tile







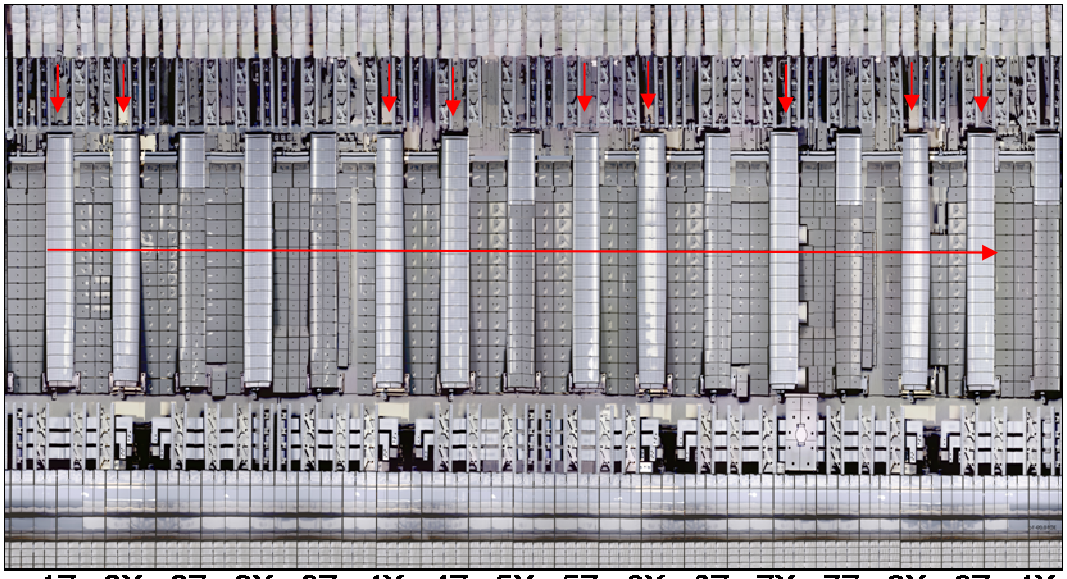
Heinola PFMC-14

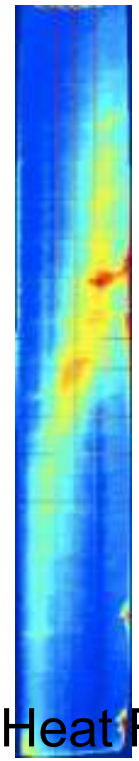
Net erosion from mid-plane IWGL tile Beryllium vs Carbon

	Net erosion rate (Atoms/s)
2005-2009 (C)	1.4e19
2011-2012 (Be)	2.3e19

Net erosion rate from one row of mid-plane IWGL tiles is higher for the beryllium wall than carbon wall
- 16 limiters for carbon wall
- 10 limiters for beryllium wall

Further analysis required to fully assess main chamber erosion and deposition





Heat Flux Distribution *Arnoux PFMC-14*

Plasma times

	Total plasma time (h)	X-point (h)	Limiter (h)
2005-2007	35	27	8
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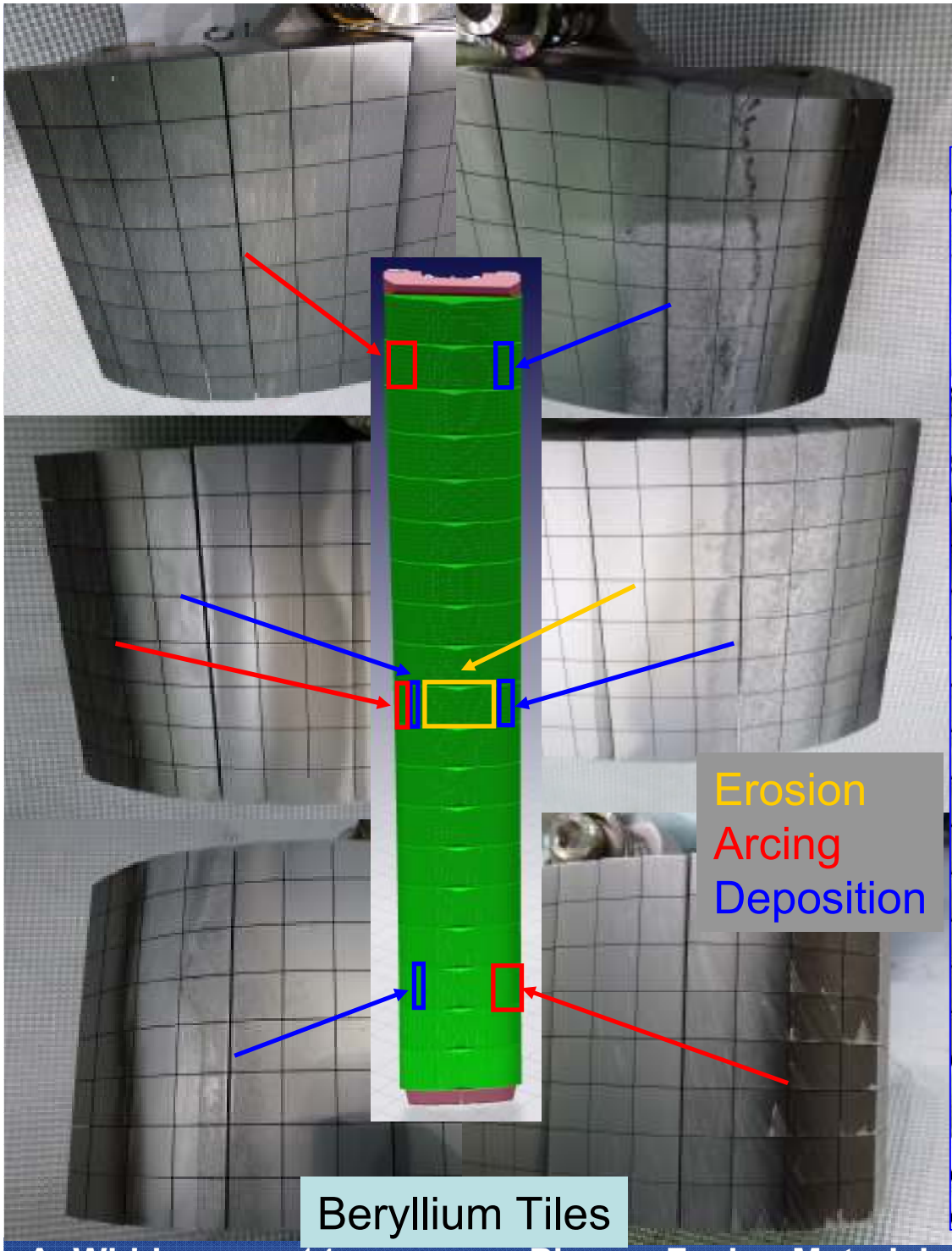
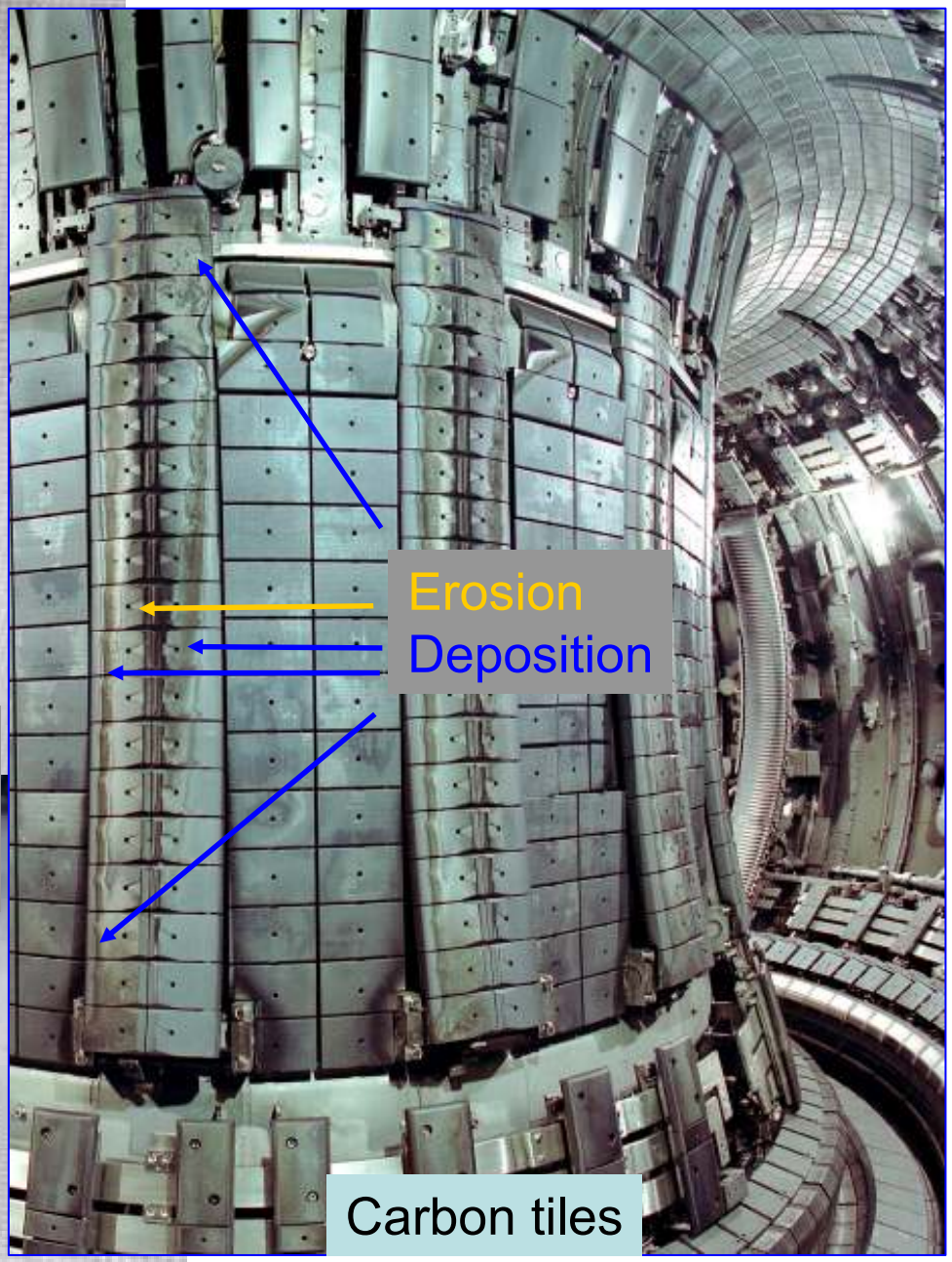
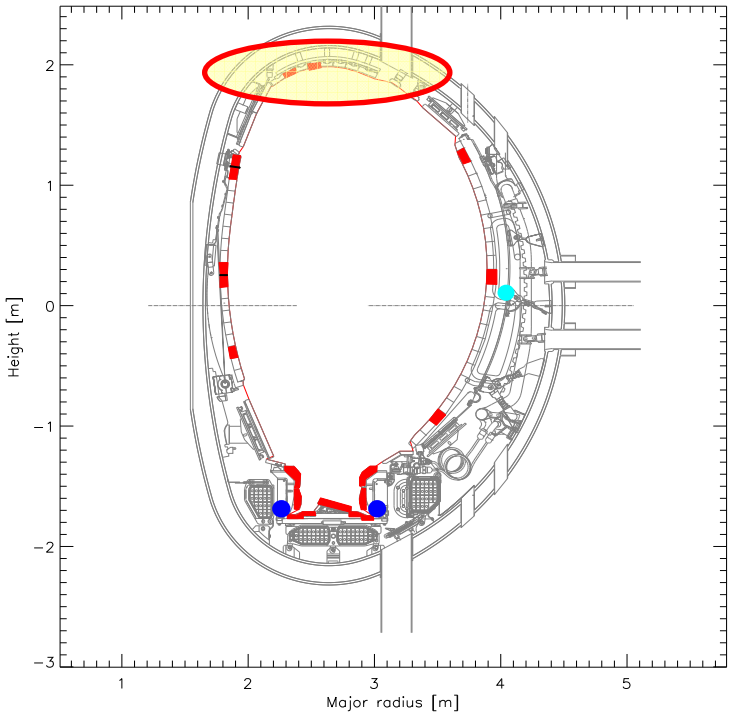
IWGL Erosion/Deposition: Beryllium vs Carbon



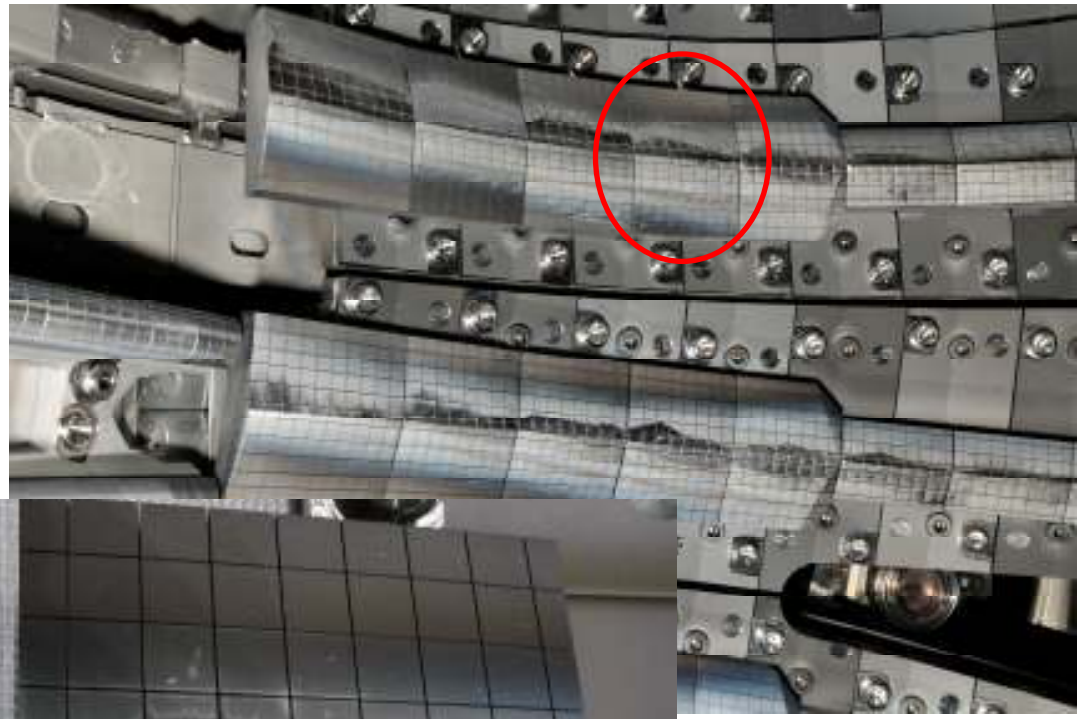


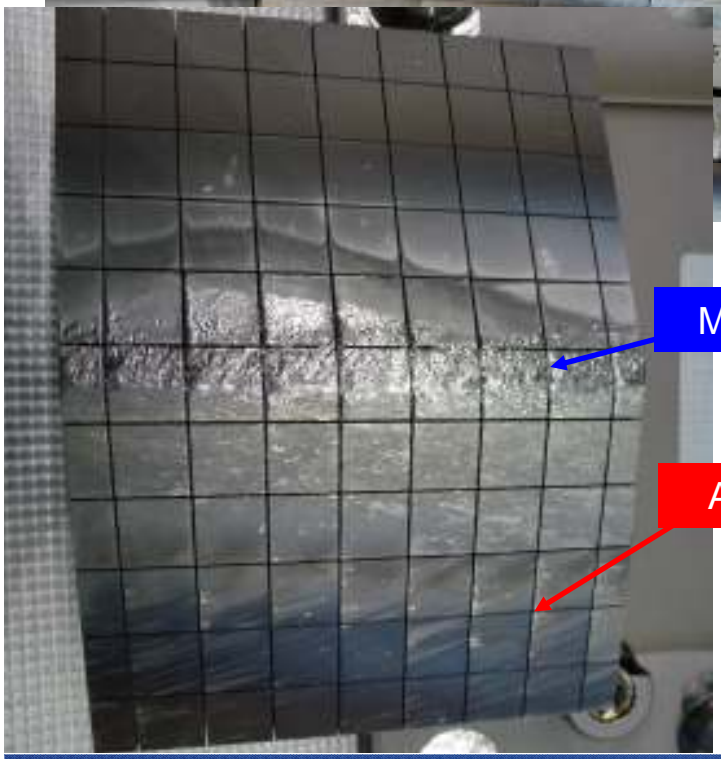
Tour of the torus

- Changes to tiles during the ILW campaigns
- First erosion and deposition data on tiles removed
  - Inner Wall Guard limiters
  - Dump plates
  - Outer Poloidal Limiters
  - Divertor tiles
  - Diagnostics in remote areas



Dump Plate

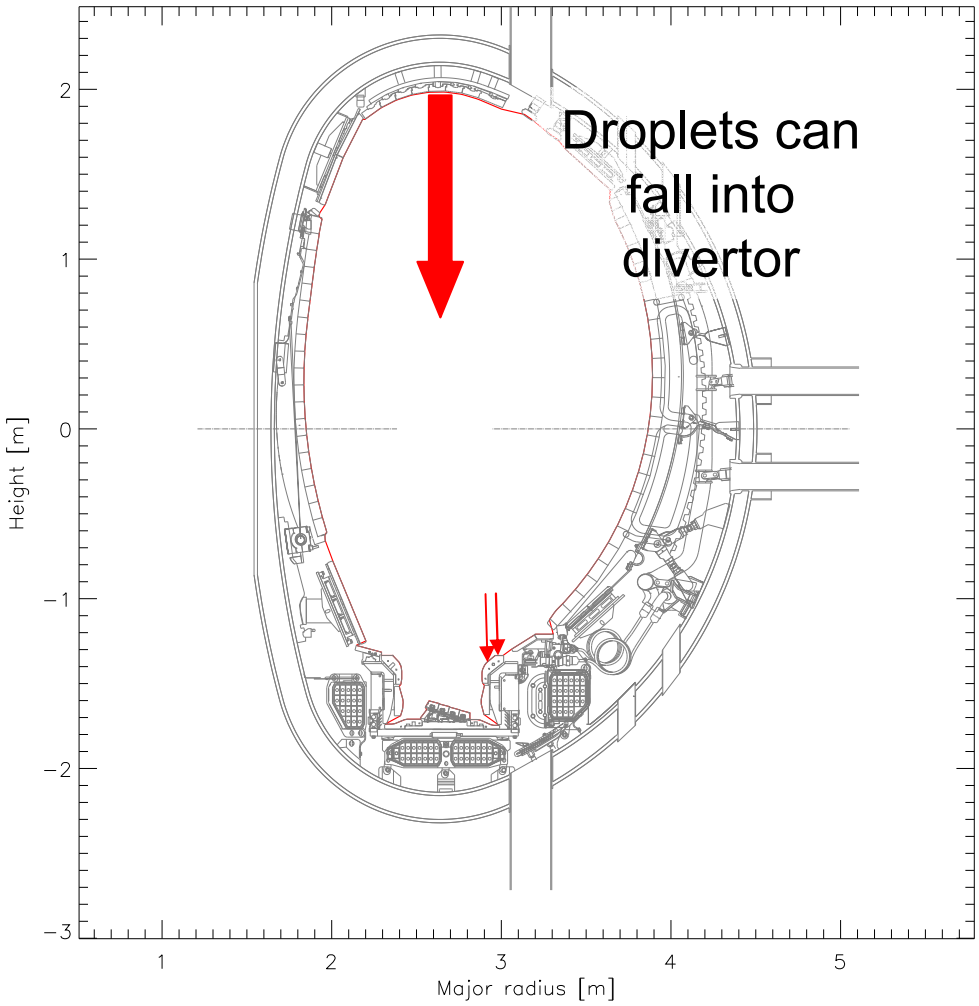


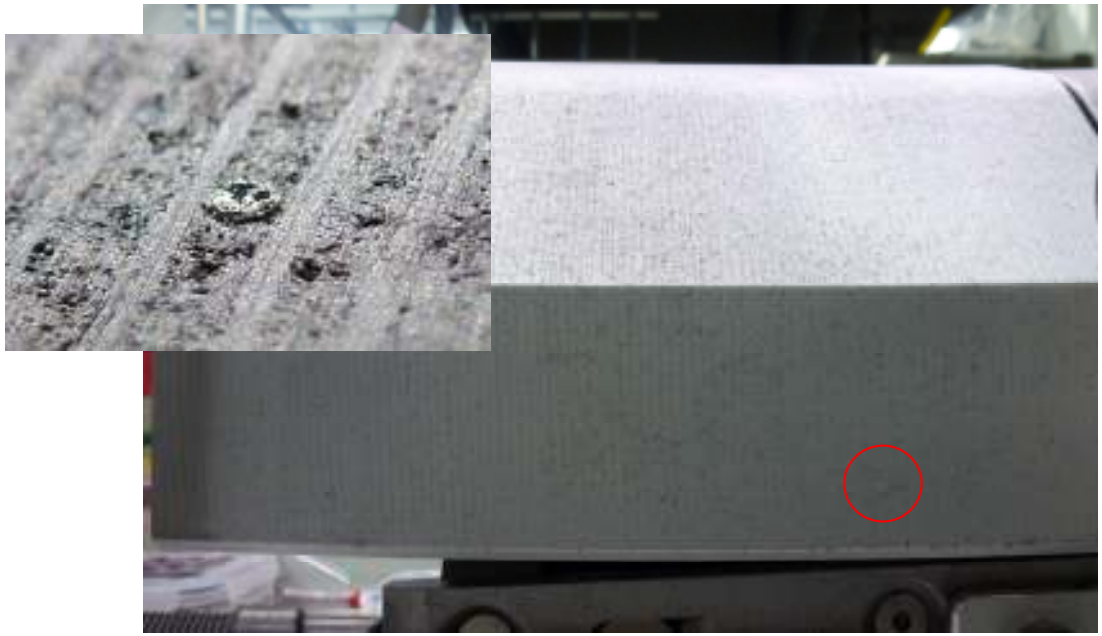


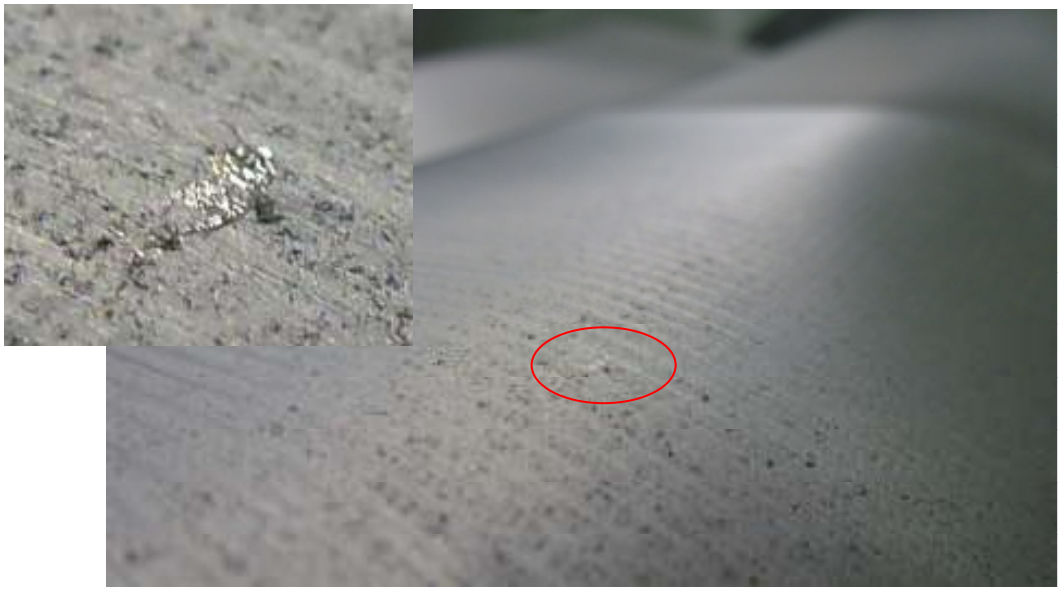
- Melt damage occurred prior to use of the disruption mitigation valve
- Toroidally uniform
- Additional source of beryllium erosion

Heinola PFMC-14
Arnoux PFMC-14 I-14

Dump Plate







<10 beryllium droplets observed on 1/12th divertor tiles closely examined

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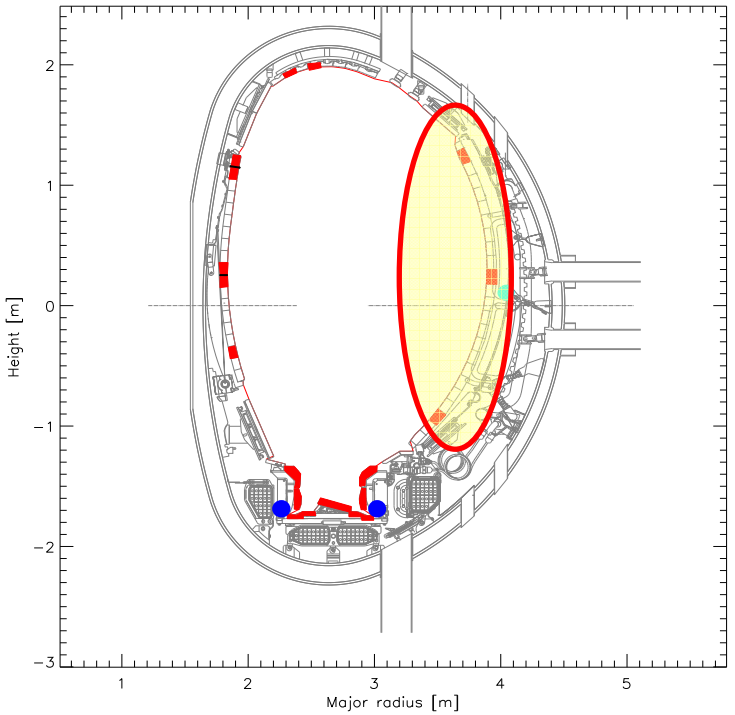
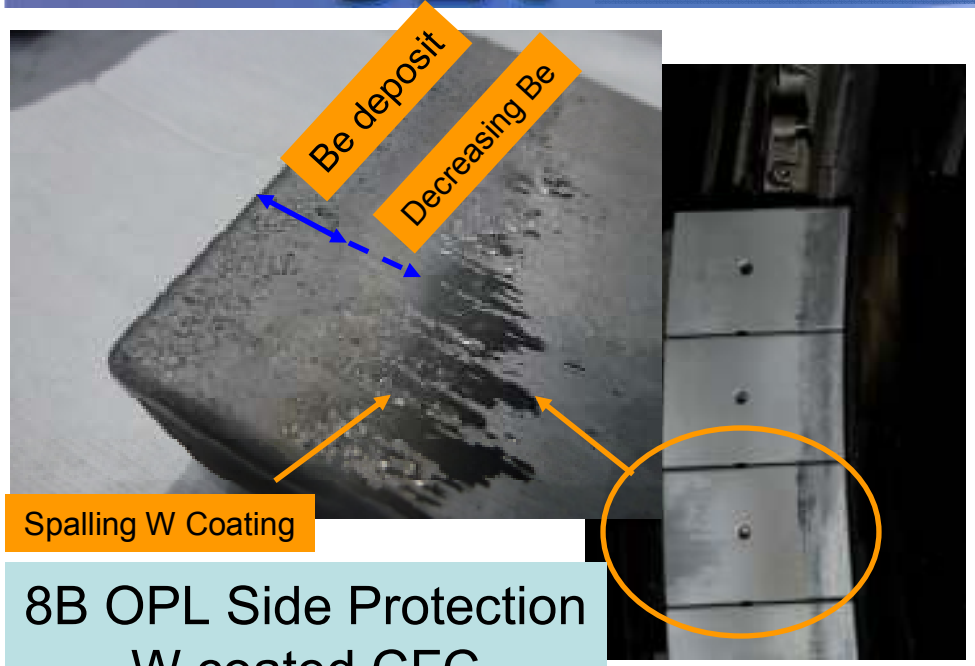
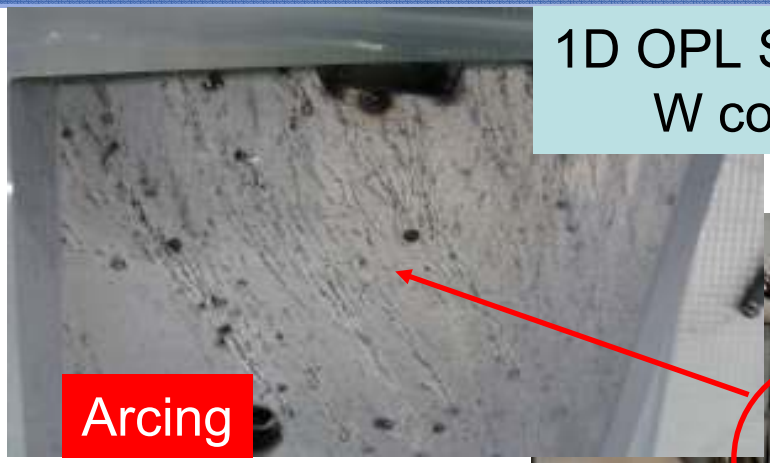


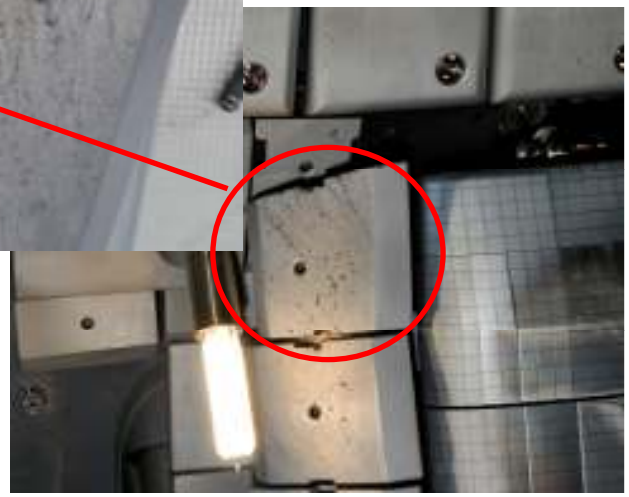
Outer Poloidal Limiter



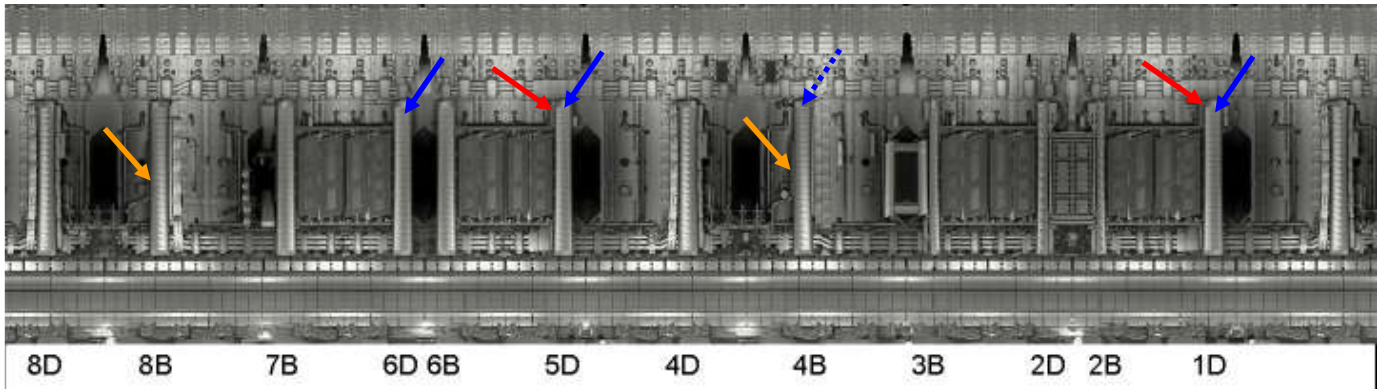
8B OPL Side Protection
W coated CFC

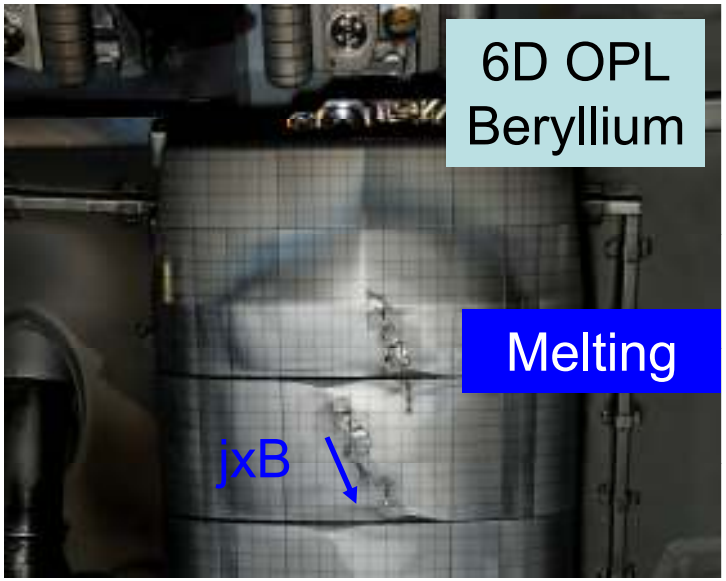


1D OPL Side Protection
W coated CFC



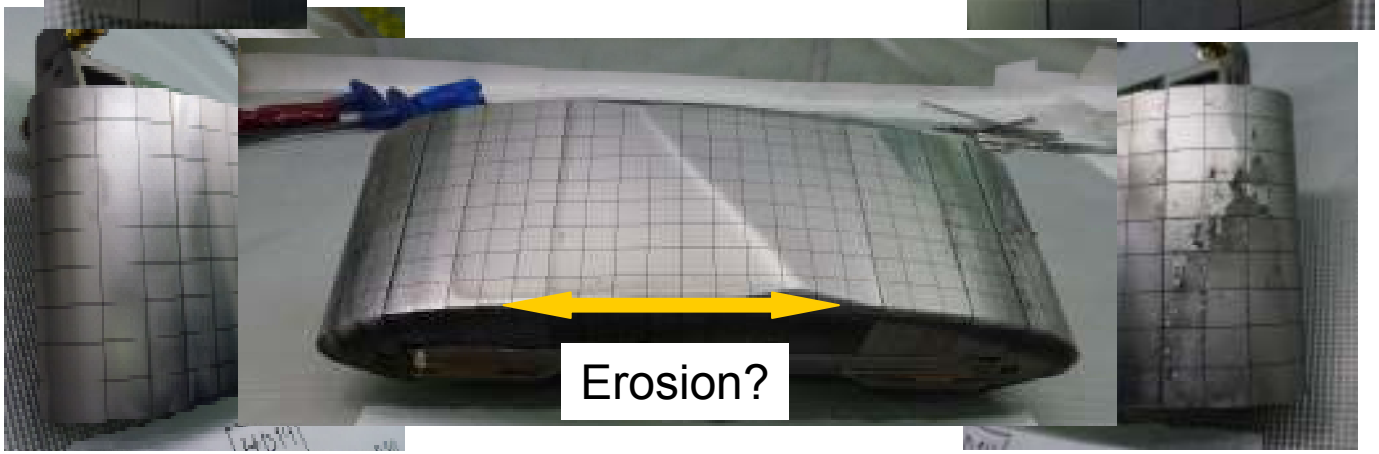
Example of Be deposition in the main chamber

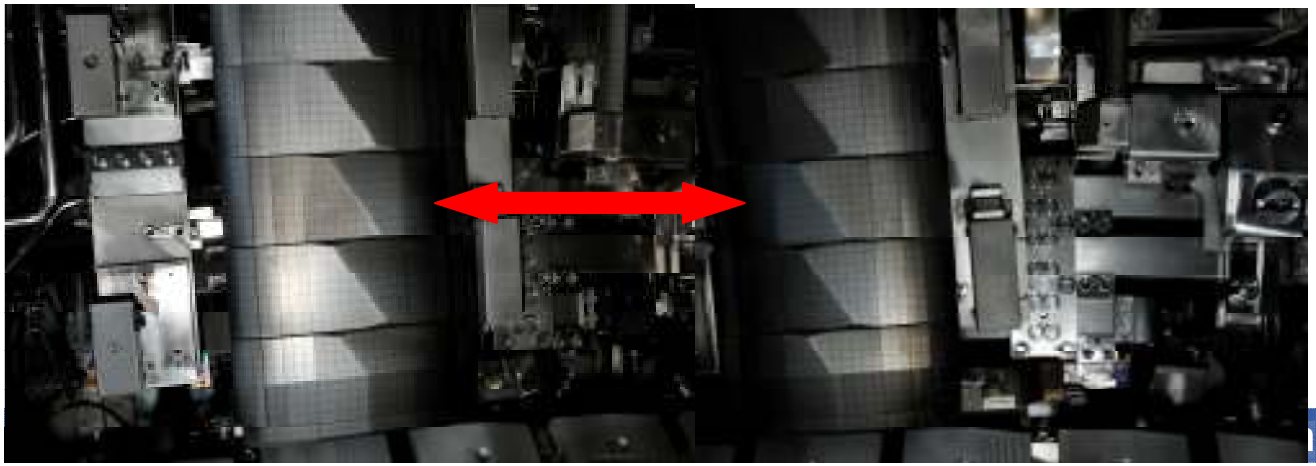


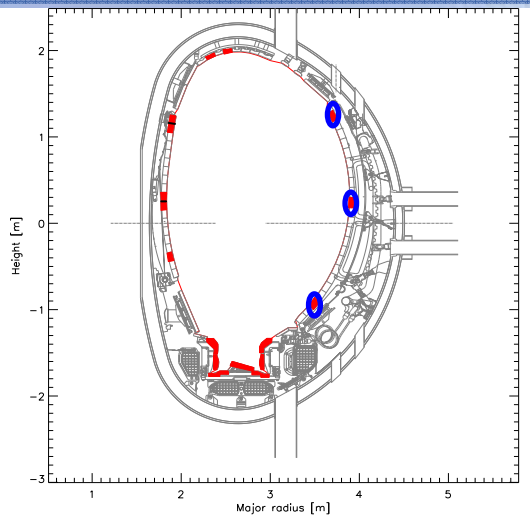


Ruset PFMC-14, Sergienko PFMC-14

Outer Poloidal Limiter







- 3 OPL tiles taken out for post mortem analysis
- Local deposition at outer ends of tile (also on side protection tiles)
- Possible erosion from centre of tile
- Spalling of marker coating at right hand end of tile
- Analysis of OPL tiles to be completed

Material Migration: Main Chamber

ILW 2011-2012

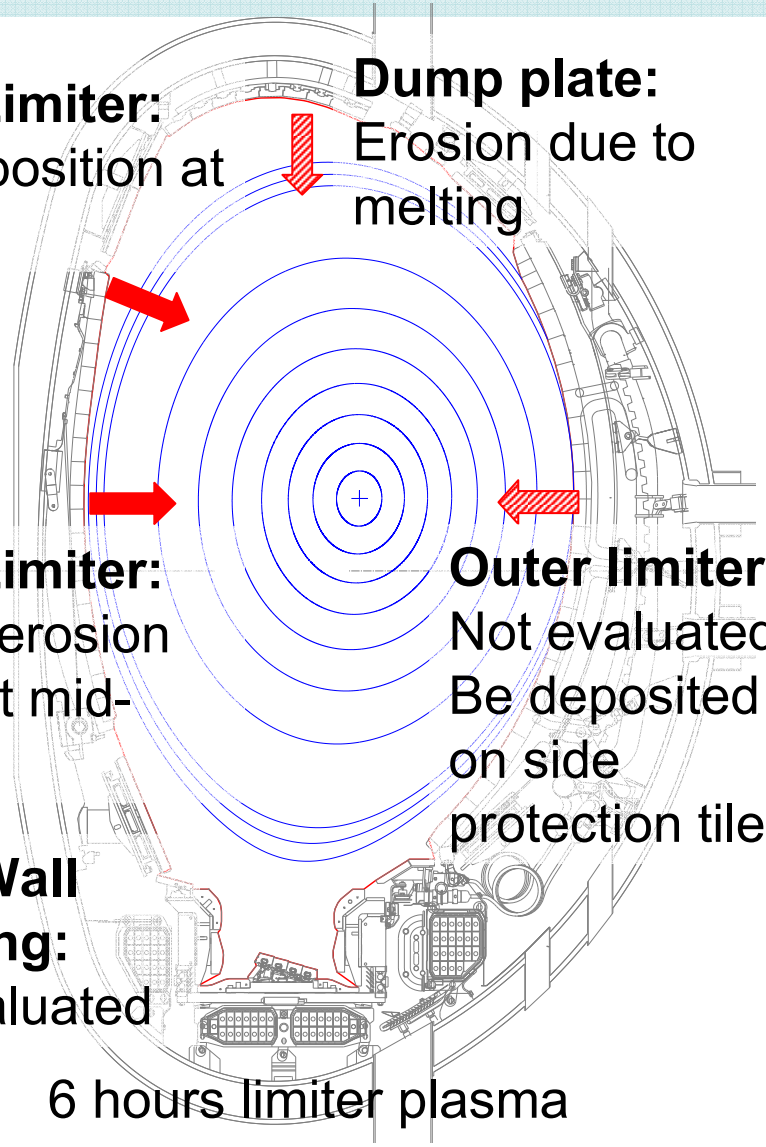
Inner Limiter:
Net deposition at top

Dump plate:
Erosion due to melting

Inner Limiter:
7g Net erosion
1 row at mid-plane

Outer limiter:
Not evaluated, Be deposited on side protection tiles

Inner Wall Cladding:
Not evaluated



6 hours limiter plasma

Carbon Wall 2008-2009

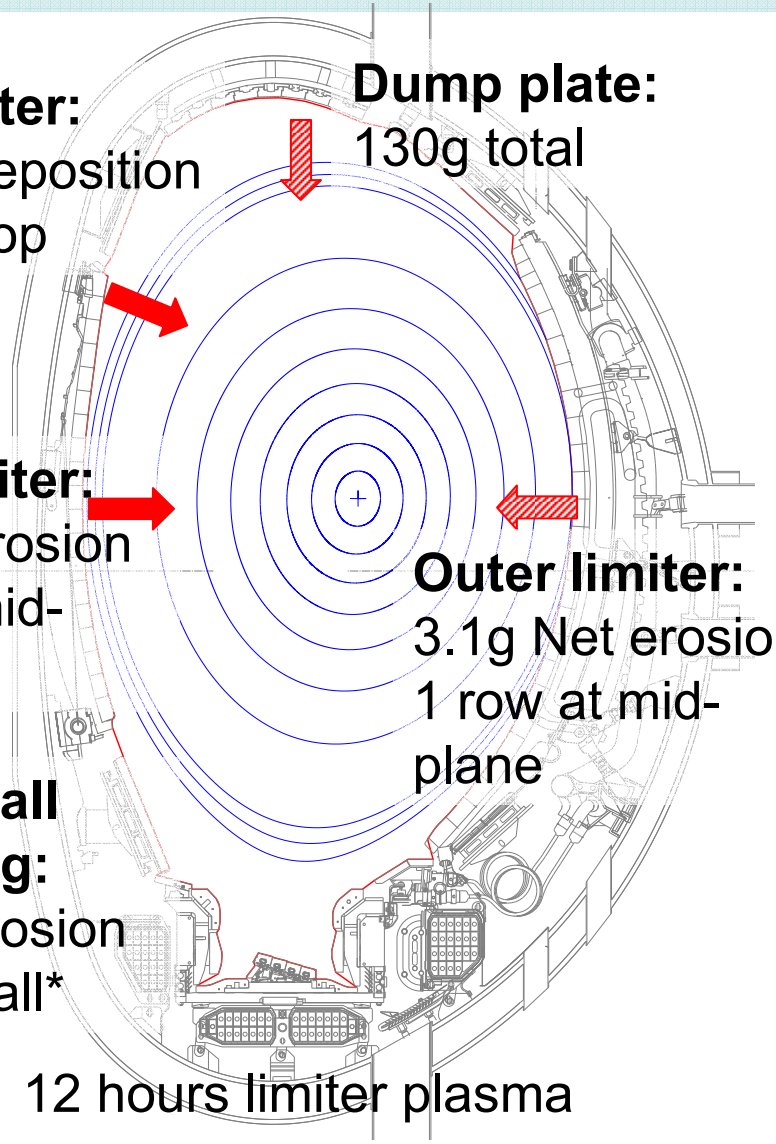
Inner Limiter:
0.8g Net deposition
1 rows at top

Dump plate:
130g total

Inner Limiter:
11g Net erosion
1 row at mid-plane

Outer limiter:
3.1g Net erosion
1 row at mid-plane

Inner Wall Cladding:
129 g erosion entire wall*



12 hours limiter plasma

*Mayer http://dx.doi.org/10.1016/j.jnucmat.2013.01.167, Widdowson http://dx.doi.org/10.1016/j.jnucmat.2013.01.179

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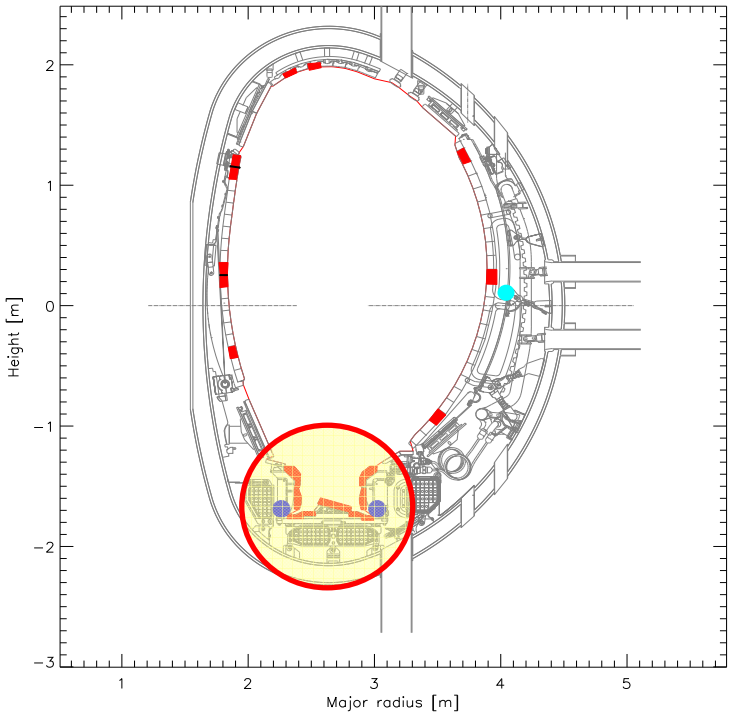
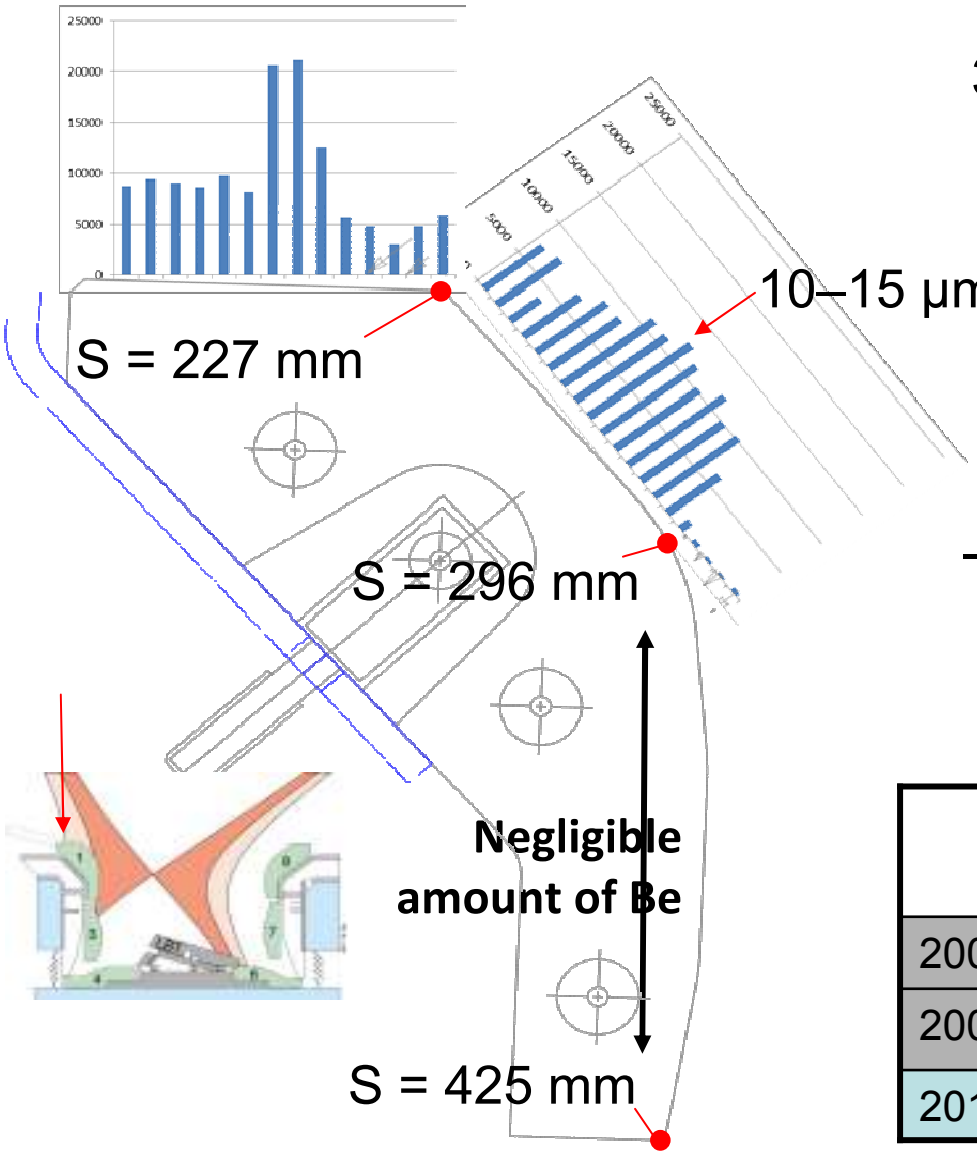
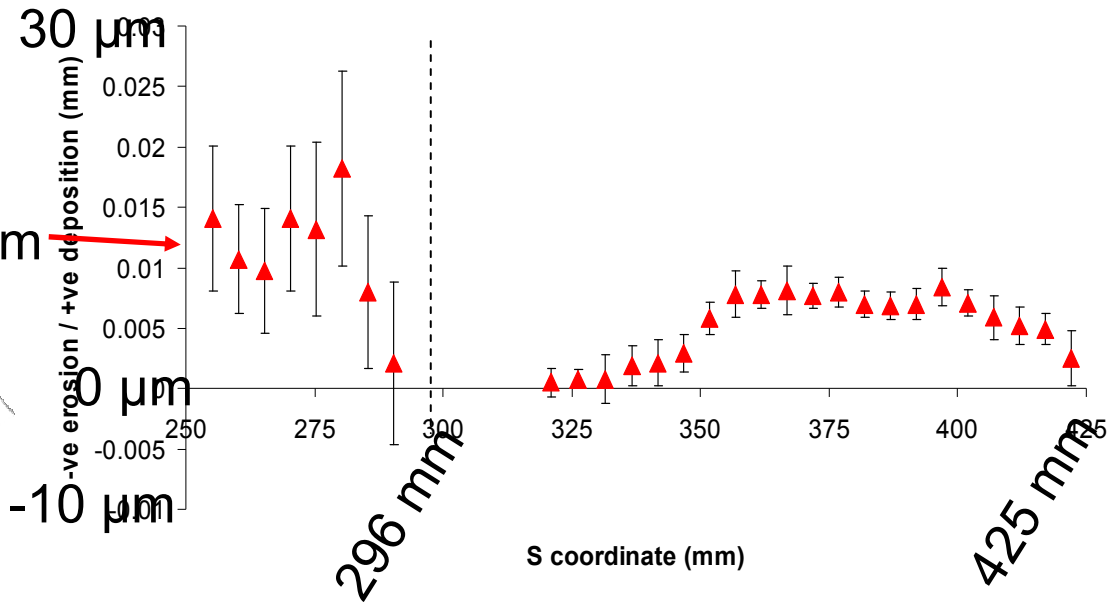


Inner Divertor



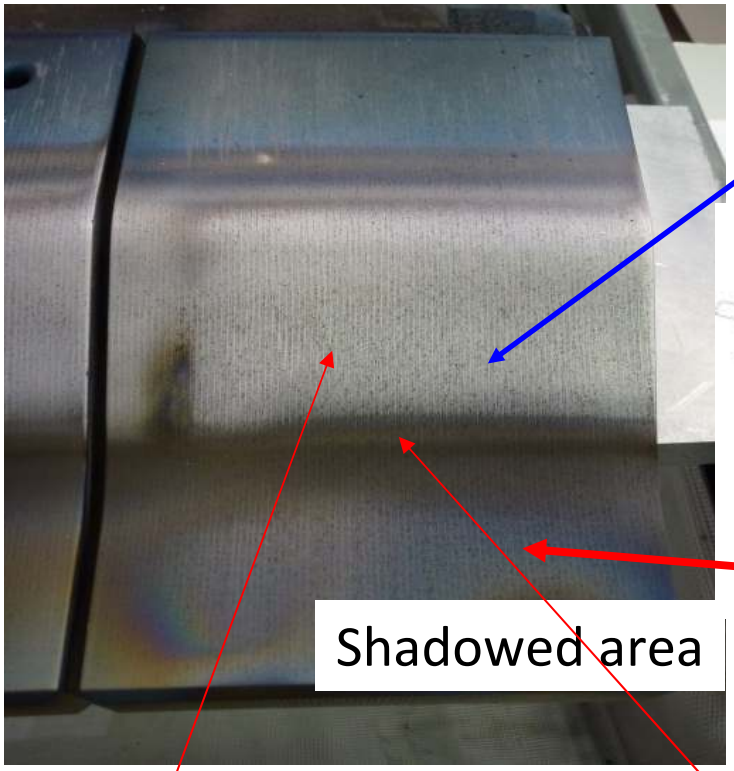


	Deposit on top of tile 1	X-point (h)	Deposition rate (atoms/cm^2/s)
2005-2007	98 µm	27	3.9e15
2008-2009	50 µm	33	1.5e15
2011-2012	≥10-15 µm	13	≥ 3.3e15

Coad PFMC-14
Heinola PFMC-14

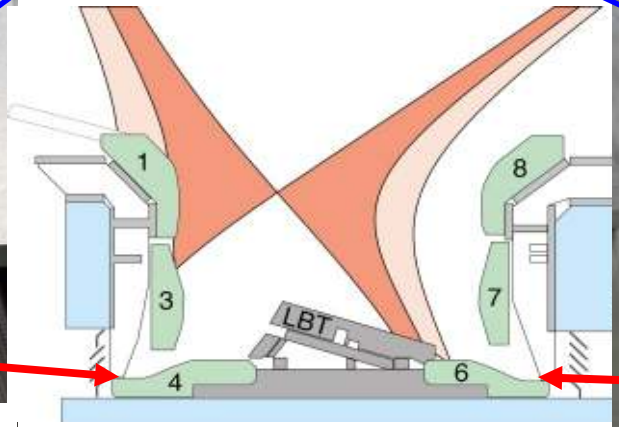
Divertor base

Inner divertor - Tile 4

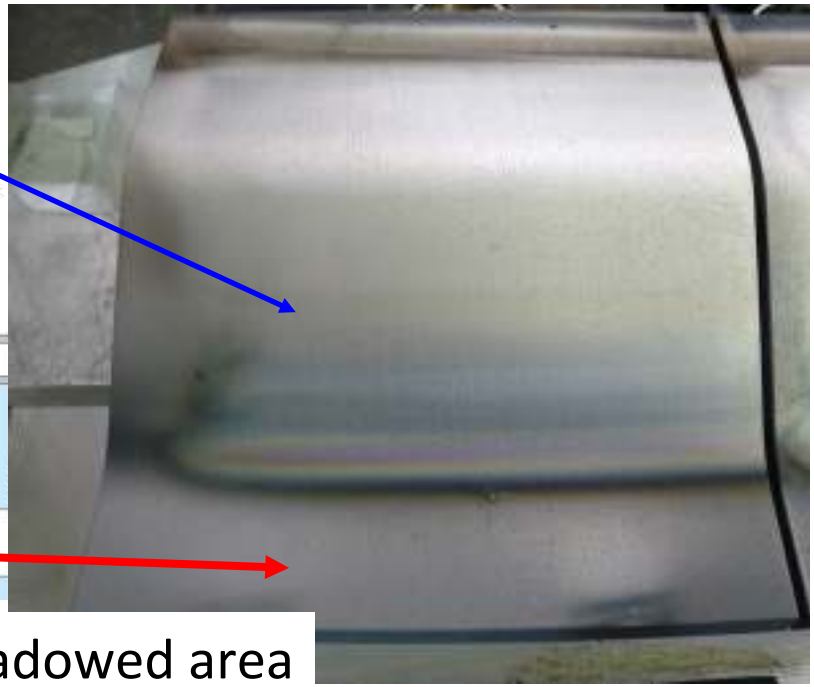


Shadowed area

Thin silvery deposit



Outer divertor - Tile 6



Shadowed area

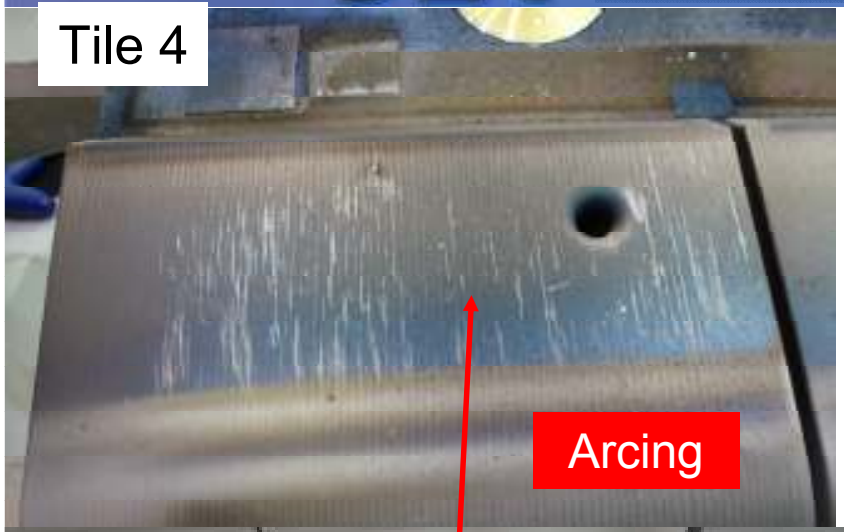
Be~3 x 10^{18} atoms cm^{-2} (~250nm)

Be ~6 x 10^{17} atoms cm^{-2} (~50nm)

Heinola PFMC-14
Coad PFMC-14

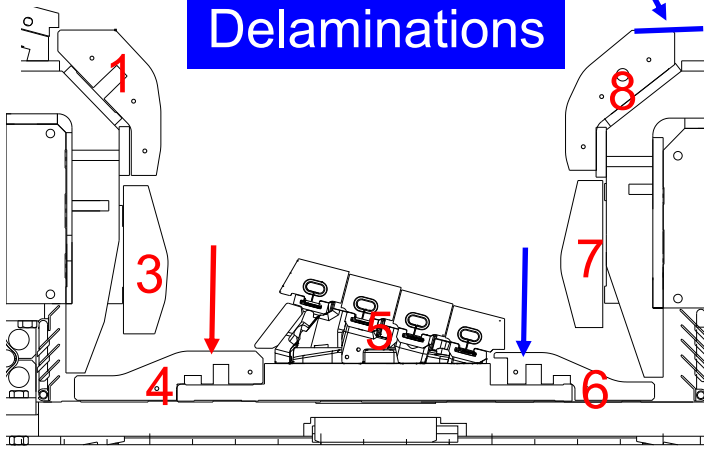
- Thin deposits have formed at the inner and outer divertor corner tiles
- No erosion/deposition observed from surface profile measurements

Tungsten Coatings on Divertor Tiles



- Tungsten coatings are largely intact
- Arcing on tile 4 around whole vessel
- Delamination on tile 8 probably due to fibre orientation on top surface

Ruset PFMC-14



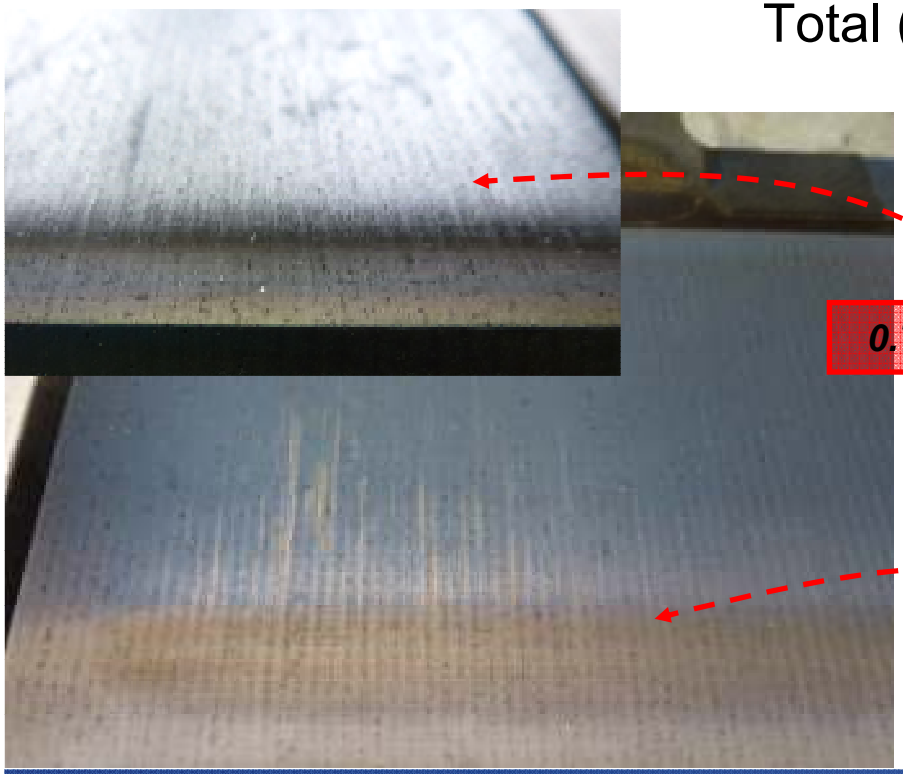
Dust

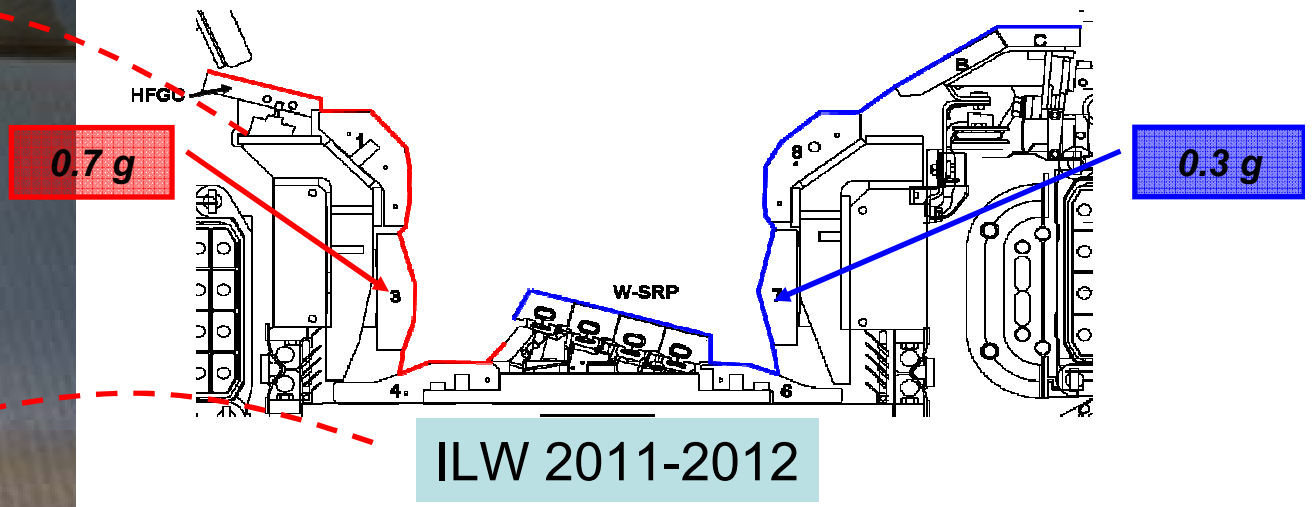
- Main source of dust for carbon wall was spalling deposits
- No thick deposits in divertor for ILW
- Continue to monitor dust production and layer growth in future interventions

Carbon Wall 2008-2009

Total (inner) = 132.4g

Total (outer) = 51.8g



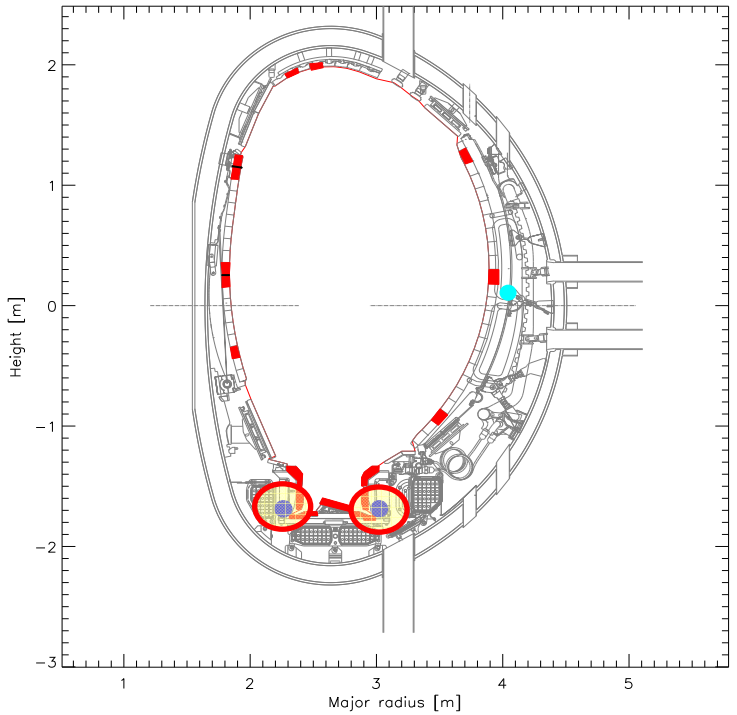


ILW 2011-2012

Heinola PFMC-14

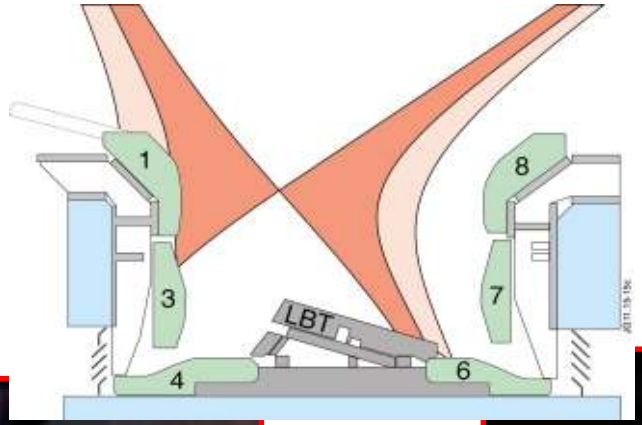
Tour of the torus

- Changes to tiles during the ILW campaigns
- First erosion and deposition data on tiles removed
  - Inner Wall Guard limiters
  - Dump plates
  - Outer Poloidal Limiters
  - Divertor tiles
  - Diagnostics in remote areas

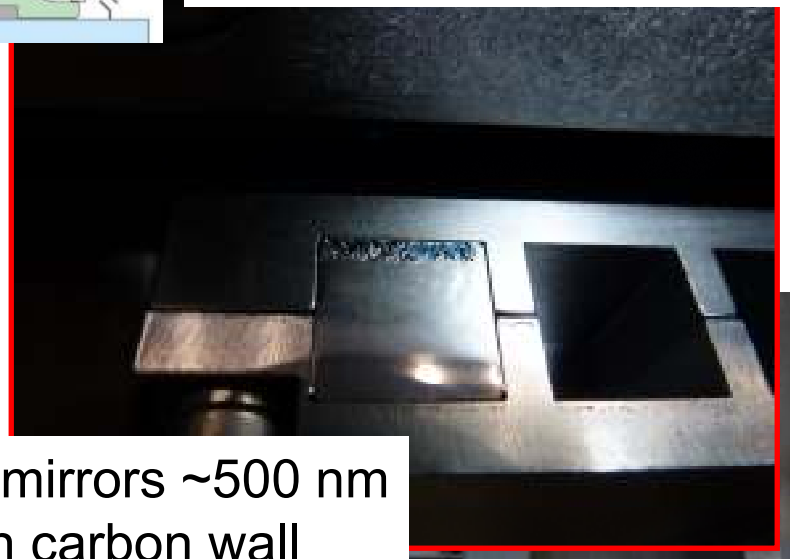


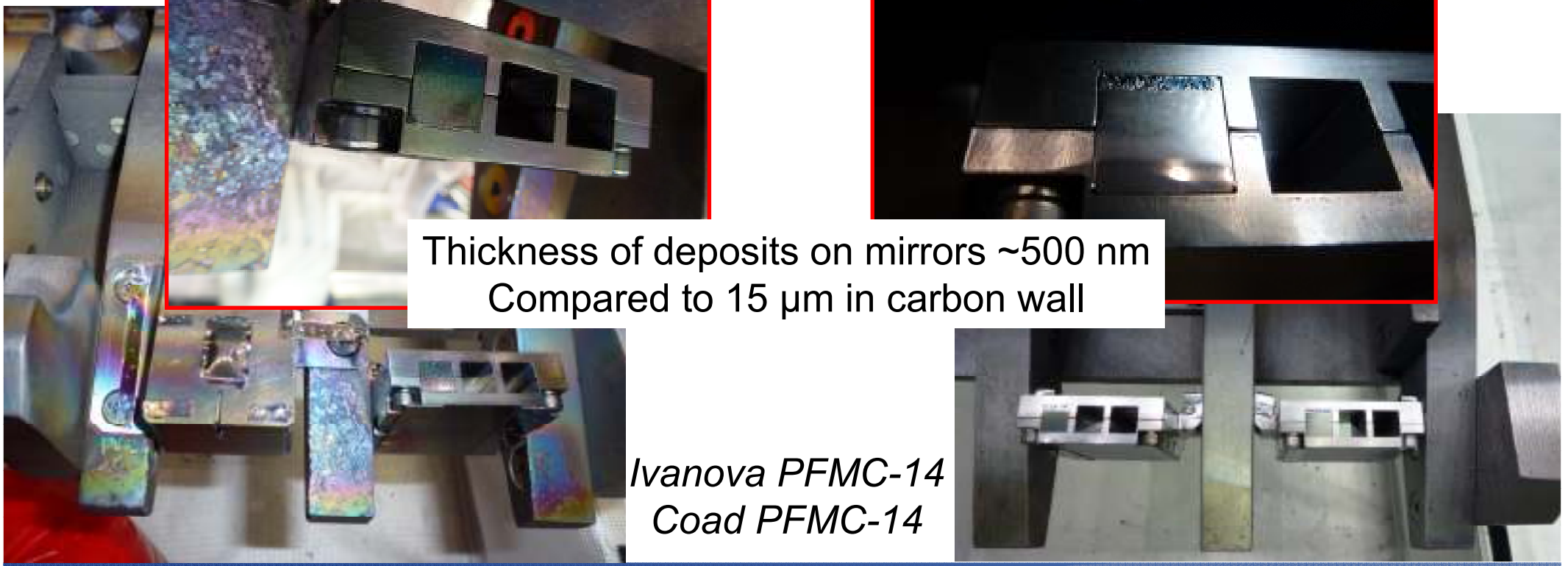
Remote divertor corners

Inner Divertor
- Thin deposits – coloured fringes
- Deposits on mirror samples contain Be, W, D, Ni, C
- Be is dominant element



Outer Divertor
- Silvery deposits
- Deposits on mirror samples contain Be, W, D, Ni, C
- C from initial operations after intervention



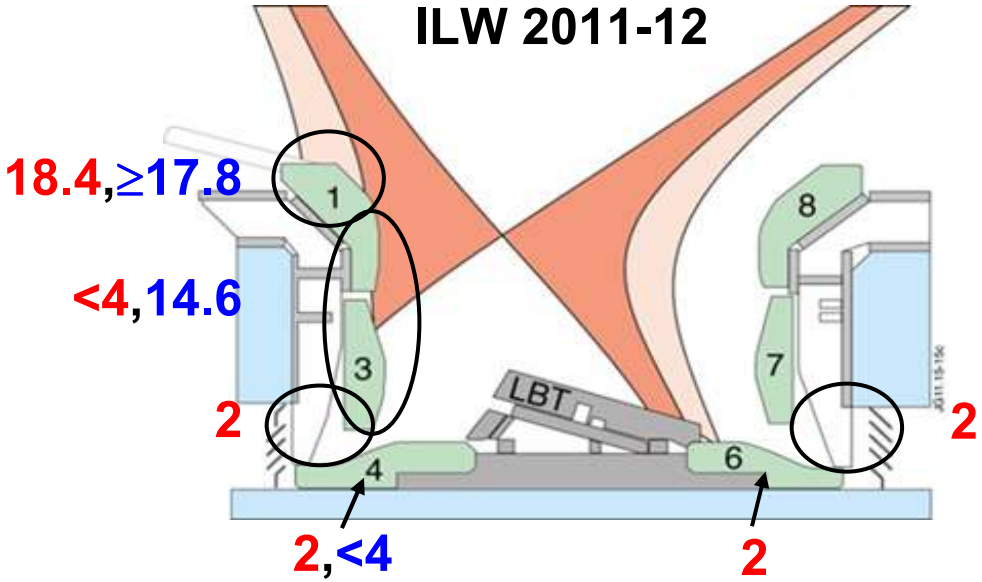


Thickness of deposits on mirrors ~500 nm
Compared to 15 µm in carbon wall

Ivanova PFMC-14
Coad PFMC-14

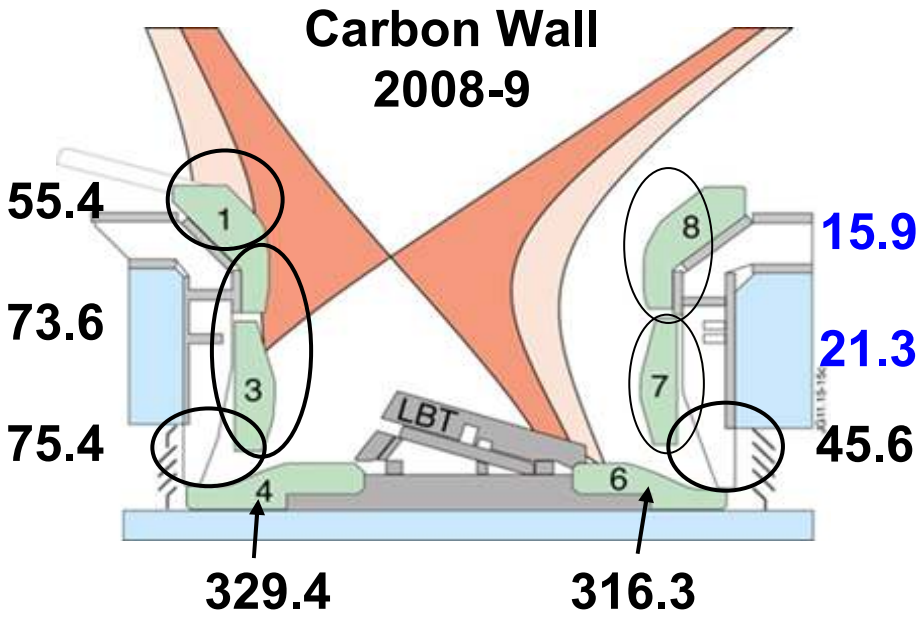
Material Migration: Divertor

Amounts of deposit in cm^3 (extrapolated to whole divertor)



For conversion to weight (or number of atoms), may be appropriate to use density of 1 g/cm^3 for C deposits but 1.85 g/cm^3 for Be, which enhances ILW figures.
Also, there may be extra Be deeper into the surface. (*Coad PFMC-14*)

Volume of deposits determined from
Ion Beam Analysis
Cross section microscopy
Surface profiling



Volume of deposit is 2 orders of magnitude lower in the divertor base
Only significant deposit in ILW divertor is top of tile 1 and possible band on tile 3

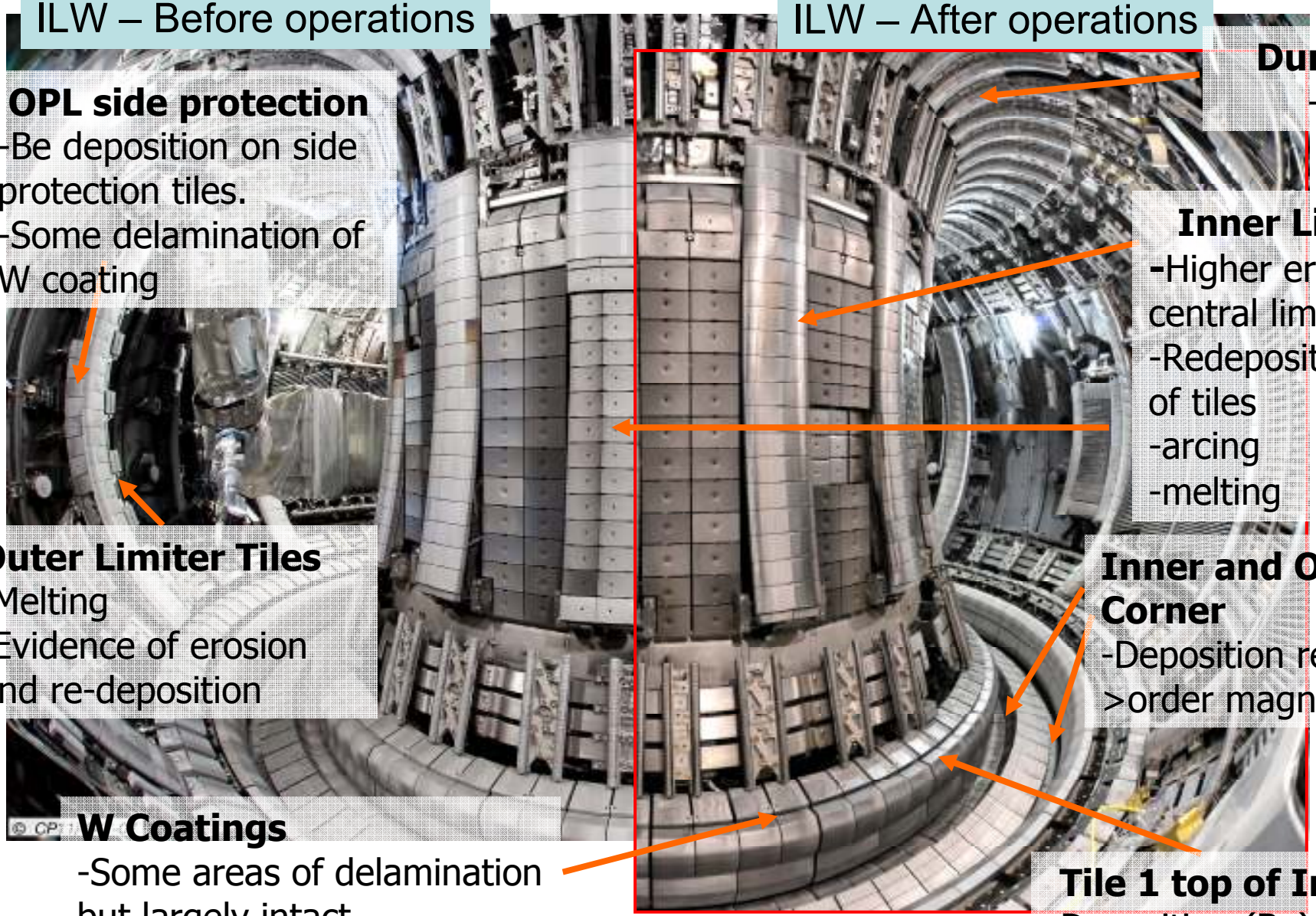
Summary

- Erosion at the inner limiter during limiter plasmas
  - Mid-plane tile shows higher erosion rate per tile when compared to carbon tile
  - Fewer inner limiters in ILW
  - Rate of Be atoms eroded only slightly higher than for C
- Re-deposition during limiter plasmas in main chamber is evident but not fully quantified
  - Ends of inner and outer limiter tiles at mid-plane
  - Net deposition at top and bottom of limiters
  - Deposition on side protection tiles of outer limiters
- Deposition during X-point plasma at the divertor base tiles at least 2 orders of magnitude lower than in C wall
  - No stepwise transport via chemical erosion to migrate material to remote areas
- Exception is deposition on top of inner divertor
  - Higher deposition rate compared to carbon wall
  - Need inner wall cladding erosion data and spectroscopy to evaluate Be source during X-point plasma
  - Possible under-estimation of outer divertor erosion in carbon wall
  - Strike point location may also account for change in distribution of deposits
- Survey of tiles surfaces show the vessel wall is largely intact
  - Some areas of delamination on W-coated CFC tiles
  - Some areas of melting on Be
  - Additional erosion sources

In-vessel Overview: Spot the Difference

ILW – Before operations

ILW – After operations



OPL side protection
-Be deposition on side protection tiles.
-Some delamination of W coating

Outer Limiter Tiles
-Melting
-Evidence of erosion and re-deposition

W Coatings
-Some areas of delamination but largely intact

Dump Plates
-Melting

Inner Limiter tiles
-Higher erosion from central limiter tile
-Redeposition on ends of tiles
-arcing
-melting

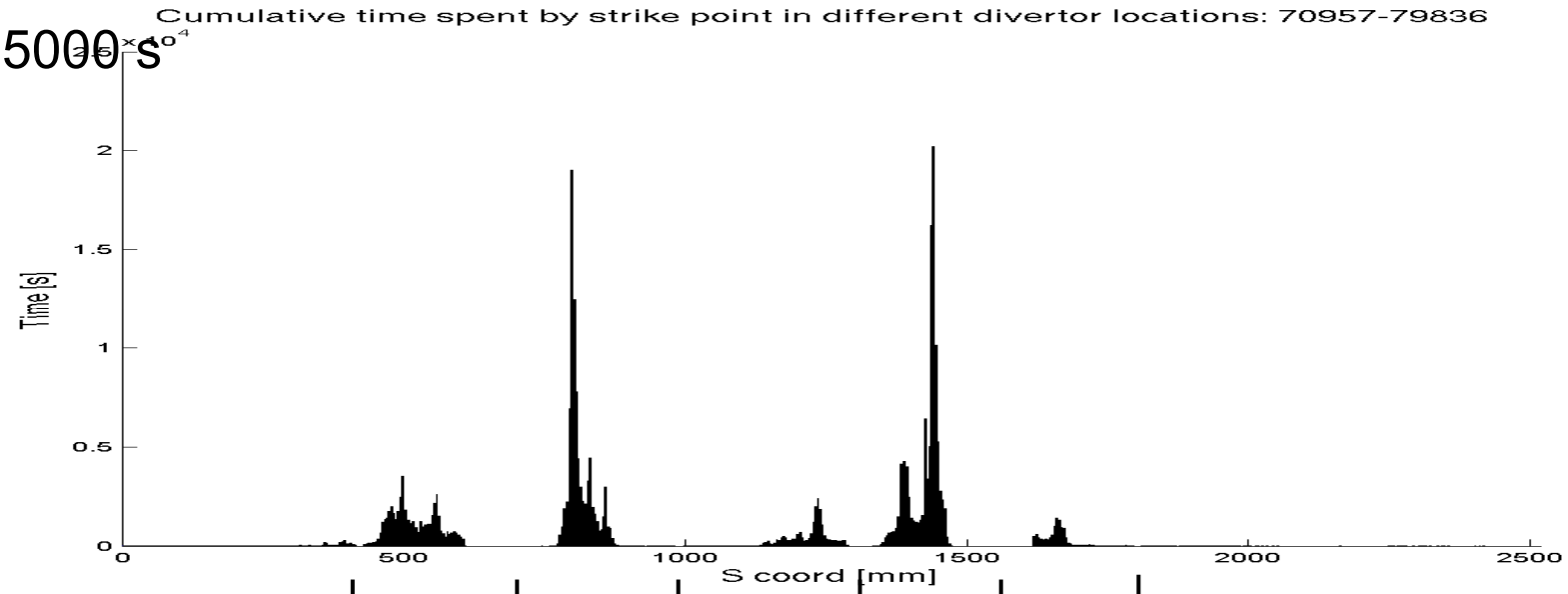
Inner and Outer Divertor Corner
-Deposition reduced by >order magnitude

Tile 1 top of Inner Divertor
-Deposition (Be) ~12μm

Comparison of strike point data

Carbon Wall 2007-9

25000 s



ILW 2010-2

4000 s